

PROGRESS REPORT NO. 9

ON

BEARING LUBRICANT ENDURANCE CHARACTERISTICS
AT HIGH SPEEDS AND HIGH TEMPERATURES

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PERIOD: October 1, 1964, through December 31, 1964

Contributors

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Project Leader:

C. J. Wachendorfer

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Submitted to:

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

LEWIS RESEARCH CENTER

21000 BROOKPARK ROAD

CLEVELAND, OHIO 44135

RESEARCH LABORATORY

SKF INDUSTRIES, INC.

ENGINEERING AND RESEARCH CENTER

KING OF PRUSSIA, PA.

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TABLE OF CONTENTS

	<u>Page</u>
INTRODUCTION	1
SUMMARY	1
CONCLUSIONS	2
DETAILS	4
1. Redirection of Remaining Effort	4
2. Continued Phase I Testing	4
Test Results	4
Discussion of Phase I Test Results	8
Lubrication of Cage Bore Guide Surfaces	9
3. Commencement of Phase II Testing	9
Discussion of Phase II Test Results	11
4. Flat Washer Cage Material Screening Tests	12
Discussion of Cage Material Screening Results	13
LIST OF REFERENCES	15
APPENDIX	16

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INTRODUCTION

This is the ninth quarterly progress report on research performed under Contract NASw-492, "A Study of Bearing Lubricant Endurance Characteristics at High Speeds and High Temperatures."

The program is being conducted in two phases, the first of which is to determine the limiting load, speed and temperature of high-temperature tool-steel 7205-size bearings lubricated with the most advanced present-day fluids. In Phase II, these bearings are being endurance tested in 30-bearing groups with the most promising lubricants, at the previously determined optimum test conditions, in order to establish their design life and reliability parameters. Tests are conducted in nitrogen blanketed high-speed high-temperature test machines developed by SKF Industries, Inc.

The wear resistance of potential high-temperature cage materials lubricated with candidate high-temperature fluids in a modified flat-washer tester is also being evaluated. Results of these tests have already been successfully applied to the high-speed high-temperature bearings previously mentioned.

SUMMARY

Phase I testing has continued with nine consumable electrode vacuum melted (CVM) M-1 steel 7205 angular-contact ball bearings and three high-temperature lubricants, viz., a highly viscous ester base oil, Sinclair Turbo S (type 1048 improved), a six-ring polyphenyl ether, Monsanto OS-138 (MLO-60-231) and a viscous hydrocarbon, Kendex Bright Stock 0846 at speeds up to 45,000 rpm, mean temperatures up to 680°F and under 365 lbs. thrust load. Check-out tests were conducted to determine the operating temperature of the rig and bearings when heated by internal heat generation only, at 45,000 rpm and to arrive at a suitable arrangement for external cooling. Runs were also made to select the most wear resistant cage materials for Phase II testing.

Phase II endurance testing has commenced with the testing of sixteen bearings out of the initial group of 30 CVM M-1 steel bearings lubricated with Esso Turbo Oil 35 at 42,800 rpm, and 500°F under

365 lbs. thrust load. Because of the current unavailability of the specific bearings and lubricants agreed upon previously for the initial Phase II testing, a suggestion for the further minor redirection of the Phase II program has been submitted to NASA and has received verbal approval.

Three cage material screening tests have been conducted in the modified flat-washer tester at 700°F using two of the currently best wear resistant materials, M-1 (Rc 60) and S-Monel (Rc 33), with a MoS₂ suspension in Esso FN-3157 and Kendex Bright Stock '0846 oils in order to explore whether MoS₂ will improve the temperature capability of these lubricants.

CONCLUSIONS

1. Phase I Testing

(a) Only short runs (3.9×10^6 rev., at 42,800-45,000 rpm) have been accomplished to date with Sinclair Turbo S ester and Monsanto OS-138 6-ring polyphenyl ether, the two new oils tested in this report period. In these short runs, Sinclair Turbo S operated at 540°F without surface distress and Monsanto OS-138 operated likewise at 560°F. Longer test runs planned for the next period will determine the performance rating of these oils.

(b) S-Monel (Rc 33) cages appear more wear resistant than M-1 (Rc 55) tool steel cages, when run at 40,000-45,000 rpm in 7205 bearings. S-Monel wear surfaces (and silver-plated steel surfaces) are being provided for future tests.

2. Phase II Endurance Testing

(a) Sixteen CVM M-1 steel bearings have completed endurance testing at 42,800 rpm, 500°F, under 365 lbs. thrust load (calculated $L_{10} = 480$ million revs.), with Esso Turbo Oil 35. Fourteen of these have exceeded 100 million revs., and of these, six have reached 230 million revs., the test termination life: all without flaking fatigue failures. The remaining two bearings were in an aborted test. Thus, there is reason to expect that under the test conditions, very few fatigue failures will occur within the planned test duration, indicating very favorable bearing performance.

(b) Silver-plated M-1 (Rc 55) tool steel cages appear to be more wear resistant than S-Monel (Rc 33) cages in these endurance tests.

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3. Cage Tests

Two per cent MoS_2 added to Esso FN-3157 (mineral oil) or Kendex Bright Stock 0846 in suspension form has not improved the ability of these fluids to prevent cage wear in M-1 (Rc 60) or S-Monel (Rc 33) specimens at 700°F.

DETAILS1. Redirection of Remaining Effort

Because of the unavailability of Socony XRM 109F highly-refined mineral oil, and also, of CVM WB49 and CVM 440C (modified) steel bearings until February, 1965, the Phase II endurance tests as outlined in (1) require further minor redirection. The proposed schedule of endurance tests for the remaining time in this contract is given in the letter to NASA reproduced in the Appendix. NASA's verbal approval of this letter has been received.

2. Continued Phase I Testing with Polyphenyl Ether, Hydrocarbon and Ester Base Lubricants

Nine CVM M-1 steel 7205 bearings assembled with either age-hardened (Rc 33) S-Monel or hardened (Rc 55) M-1 steel cages (Enclosures 1, 2, 3 and 4) and CVM M-1 steel balls were tested at speeds up to 45,000 rpm, mean temperatures up to 680°F and under 365 lbs. thrust load (AFBMA computed L_{10} life = 480×10^6 revs.). The inner race groove of these bearings was specially ground and honed to improve their surface finish. The resulting roughness measured across the groove is of the order 3-5 microinches, rms. All bearings tested had an average radial cage play between .003" to .008" and an unmounted radial looseness of 40-52 microns. The three oils used to lubricate the test bearings were: Sinclair Turbo S (type 1048 improved), a high viscosity ester base oil, Monsanto OS-138 (MLO 60-231), a six-ring polyphenyl ether, and Kendex Bright Stock 0846, a hydrocarbon. The temperature-viscosity characteristics of these lubricants are shown in Enclosure 5. A summary of the test results appears in Enclosure 6 and the bearing dimensions before test are given in Enclosure 7.

Test Results

Sinclair Turbo S (type 1048 improved), a highly viscous ester base oil, was used to lubricate the bearings in test run #52 which was conducted at 42,800 rpm and under 365 lbs. thrust load. The bearings were assembled with bore recessed hardened (Rc 55) M-1 steel cages (Enclosure 1). Bearings numbered 161 and 163 were run for the initial 0.7 hours (1.8×10^6 revs.) of the test during which it was observed that the temperature of the load end bearing had risen well above the control temperature of 550°F, to 618°F (oil viscosity = 1.04 cs). Excessive oil loss was also taking place through the load plug clearance bore. Attempts to retard the

oil loss by increasing the N₂ flow which seals the clearance around the load plug and/or opening the by-pass valve were unsuccessful. Shortly thereafter, the test was abruptly terminated by the vibration sensitive switch. Examination of the bearings indicated that the load end bearing had smeared races and balls but the drive end bearing whose temperature had increased to 580°F (oil viscosity = 1.15 cs) was in good condition.

The test was resumed for an additional 1.2 hours (3.1 x 10⁶ revs.) operation with a new bearing, #164, on the load end. Oil continued to leak excessively from the load plug clearance bore and the bearing temperature rose above the control level. Make-up oil was in the process of being added to the system when the pressure dropped and automatically shut the tester down. The tester was disassembled. The drive end bearing had glazed and flaked with excessive wear taking place on the inner race lands. The cage bore wear was 1.6 mils and was considered slight (Enclosure 8). The load end bearing had smeared races and balls and its cage had worn excessively (24.2 mils) in the bore (Enclosure 9). An analysis of this run showed later that the temperature instability was a continuing risk in operation above 40,000 rpm, which could be avoided by fan cooling of the housing. This method will be discussed below. Oil leakage was due to excessive clearance on the particular load plug used and was overcome by replacing it.

It was noted in the Phase I tests reported herein and those reported earlier (1) that only a small portion of the heater capacity was required to maintain the bearings at 600°F when operating at speeds between 40,000 to 45,000 rpm and that this rendered control of the temperature critical. Under the test load and speed conditions of 365 lbs. thrust and approximately 45,000 rpm, bearings lubricated with Kendex Bright Stock 0846 have in the past operated at 540°F without any external means of heating and employing only natural air cooling; whereas, bearings run with Esso Turbo Oil 35, which is less viscous than the Bright Stock, have been controlled to approximately 500°F utilizing a 20% heater output to the housing block and natural air cooling. Several additional checkout tests were conducted in this report period in which various means of cooling were employed. They consisted of partially or fully closing the by-pass and/or the inlet return valves which control the amount of oil recirculating to the bearings, not heating the oil supply in the reservoirs prior to recirculation to the bearings, and increasing the bearing's radial cage clearance and the internal clearance between the screw pumps on the test shaft and the shaft liner. None of these methods were successful.

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However, it was observed that bearing temperatures could be maintained at approximately 500-550°F (depending upon the viscosity of the lubricant) by externally air cooling the housing block with one fan located on each side of the test machine while providing an adequate heat input to the housing block for control (about 20% heater capacity).

In test run #53, the bearings were lubricated with Monsanto OS-138 (MLO-60-231), a six-ring polyphenyl ether, and run at speeds up to 45,000 rpm. Bore recessed hardened M-1 (Rc 55) cages as shown in Enclosure 2 were assembled with the bearings. In order to prevent the bearing temperatures from rising above the control temperature of 600°F, one fan was employed to increase dissipation of the heat generated in the housing block. (It was found in the subsequent testing described above that two fans, one on each side of the tester, are required to obtain satisfactory heat removal.) Copper inhibitors in the form of sheets and screening were placed in each oil sump and all the gasketing used for this test was made from Du Pont polyimide, type SP-1 plastic, in order to prevent decomposition of the oil. Special care was also taken to see that the test machine was scrupulously clean prior to startup. The test ran for 1.3 hours (2.2×10^6 revs.) during which the load end bearing temperature rose to 695°F (oil viscosity = 1.15 cs). At that time, the vibration sensitive switch shut the machine down. Examination of the bearings revealed that the load end bearing had glazed and flaked (Enclosure 10). Its cage bore wear was 2.5 mils and was considered slight. The drive end bearing as shown in Enclosure 11 was in good condition and its cage bore wear was not appreciable (0.1 mils).

Test run #54 was conducted with two fans dissipating the heat generated in the housing block and with Kendex Bright Stock 0846, an oil which will lubricate adequately at approximately 580°F. Straight bore, age-hardened (Rc 33) S-Monel cages shown in Enclosure 3 were assembled with the bearings. The test was conducted at 45,000 rpm, mean temperature up to 550°F (oil viscosity = 1.70 cs) and under 365 lbs. thrust load. After 33.0 hours (89.1×10^6 revs.) operation, the tester was shut down because of excessive vibration. Examination of the bearings at this time indicated that both bearings were in good condition and very slight cage bore wear had taken place but two of the cage pockets in the load end bearing had cracked. This cage was replaced with a bore recessed hardened (Rc 55) M-1 steel cage (Enclosure 1) and the test continued. After an additional 2.2 hours operation or a total accumulative running time of 35.2 hours (95.0×10^6 revs.) on the

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test bearings, the load end bearing temperature increased rapidly to 655°F (oil viscosity = 1.17 cs). The test was then discontinued and upon disassembly of the tester, it was observed that the load end bearing had glazed and flaked with severe land wear taking place on its inner race (Enclosure 12). The bore of its cage had worn 3.0 mils. The drive end bearing was in good condition and its cage bore wear was very slight (Enclosure 13). Up until the point of failure, both bearing temperatures could be well controlled at 550°F and 45,000 rpm, using this lubricant and two fans to cool the housing block.

Since the hardened (Rc 55) bore recessed M-1 steel cages reported in (1) seemed inferior for wear performance to those manufactured from age-hardened (Rc 33) S-Monel, several check-out tests were conducted using CVM M-1 steel bearings constructed with hardened (Rc 55) M-1 steel bore recessed cages (Enclosures 1 and 2) and Kendex Bright Stock 0846 oil. The bearings were run in both the variable and the constant speed test machines at 42,800 rpm, mean temperatures up to 550°F and under 365 lbs. thrust load. Results of these tests indicate that severe inner race land wear takes place with these cages no matter which test machine is used or if the cage radial clearance is increased from .002"/.003" (Enclosure 2) to .006"/.008" (Enclosure 1). As further evidenced by the Phase I tests reported herein, cages manufactured from hardened (Rc 55) M-1 steel experienced considerably more bore and inner race land wear than those manufactured from age-hardened (Rc 33) S-Monel. In fact, in test run #54, which was conducted with Kendex Bright Stock 0846 oil at 45,000 rpm, mean temperatures up to 550°F and under 365 lbs. thrust load, the CVM M-1 steel bearings ran without surface distress for 33.0 hours (89.1×10^6 revs.) when assembled with the straight bore hardened (Rc 33) S-Monel cages shown in Enclosure 3. After replacing one of these cages (because it had cracked pockets) with a bore recessed hardened (Rc 55) M-1 steel cage (Enclosure 1), the bearing in which it was assembled lasted only an additional 2.2 hours (5.9×10^6 revs.) before it glazed and flaked. In addition, the inner race lands were grooved and the cage bore had worn 3.0 mils.

In order to preclude that a difference in design may account for the better performance of the S-Monel cages, test run #55 was conducted under identical test conditions as run #54 but with the bearings assembled with bore recessed age hardened (Rc 33) S-Monel cages as shown in Enclosure 4. Except for the material and heat treatment, these cages were identical in design and manufacture to the bore recessed hardened (Rc 55) M-1 steel cage used in the previous test. After 90 hours (243.0×10^6 revs.) the bearings were in good condition and only a maximum of 1.0 mils bore wear

had taken place in the cages (Enclosures 14 and 15).

Discussion of Phase I Test Results

Operation of the test machines at speeds between 40,000 to 45,000 rpm has indicated that enough heat is generated by the test bearings themselves to maintain their temperature in the vicinity of 540°F. The stabilized temperature depends primarily upon the speed of operation and the viscosity of the test lubricant, inasmuch as the heat generation in the assembly decreases if lower viscosity lubricants are used. This effect is attributed to the reduced viscous loss with lower-viscosity oils in the screw pump and other sliding combinations.

Increasing the clearances between the rotating and stationary components of the bearings and the test machine and/or reducing the oil temperature in the reservoirs and the amount of oil recirculating to the bearings did not significantly affect the stabilized operating temperature of the bearings at speeds between 40,000 to 45,000 rpm. Adequate control of the bearing operating temperatures using 15-20% of the heater capacity has been obtained at temperatures down to 500°F by externally air cooling the test machines using fans.

Test run #52 is not considered a true indication of the performance of Sinclair Turbo S (type 1048 improved) oil since efforts to reduce the amount of oil loss by controlling the N₂ flow to the load plug and the flow of oil recirculating to the bearings were being made during the test. A retest of this lubricant at mean temperatures up to 600°F and under controlled test conditions is planned during the next period.

The six-ring polyphenyl ether, Monsanto OS-138, which was used to lubricate the bearings in test run #53 does permit glazing-free operation at mean temperature up to 560°F for 1.3 hours (2.8×10^6 revs.). Perhaps a more extended life would have been realized if a cage of better wear performance would have been used, thereby preventing debris formation and some of the heat development in the bearing. The coking tendencies of this oil seemed to be similar to those of the Monsanto OS-124 five-ring polyphenyl ethers or a proprietary blend (PWA 524), tested previously (1,2). The oil was black after the test, and there was only a small amount of black carbon deposit on the oil filter screens (a much heavier deposit was experienced in earlier tests with the five-ring polyphenyl ethers). A retest of the 6-ring polyphenyl ether at mean temperatures up to 600°F will be conducted, using S-Monel or silver-plated cages, within the following report period.

Test runs #53 and #54, which were conducted to improve control of the temperature of the test machines at high speeds, further substantiate that Kendex Bright Stock 0846 will permit the bearings to operate without surface distress at mean temperatures up to 550°F, if inner race land and cage wear can be controlled.

Lubrication of Cage Bore Guide Surfaces

Recent test results with CVM M-1 bearings at 40,000 to 45,000 rpm obtained with either age-hardened (Rc 33) S-Monel or hardened (Rc 55) M-1 steel cages indicate a preference for the softer S-Monel material, and increasing the radial clearance of the hardened (Rc 55) M-1 steel cages from .002"/.003" to .006"/.008" does not improve the performance of the M-1 cages. (Previous test results at 20,000 rpm (3) showed that hardened (Rc 65) M-1 steel cages are more wear resistant than annealed (Rc 24) M-1 cages of similar design.)

Since there are no more age-hardened (Rc 33) S-Monel cages currently on hand, continued Phase I and Phase II testing will be conducted with hardened (Rc 55) bore recessed M-1 steel cages which have been silver plated or sprayed with an S-Monel coating in their bores. A new supply of age-hardened (Rc 33) bore recessed S-Monel cages is expected to be available within the next month. Some bearings with silver-plated M-1 steel cages were run in Phase II tests described below and have performed well. It has also been SKF's field experience that silver-plated cages perform well at high speed and temperatures. No experience as yet has been gained with S-Monel coated cages but it is intended to use them in a few Phase I tests to determine whether they are equivalent to solid S-Monel cages for use in endurance tests.

3. Commencement of Phase II Testing

Endurance testing of a group of 30 CVM M-1 steel bearings (the first endurance group) has begun at 42,800 rpm, mean temperatures of 500°F and under 365 lbs. thrust load (C/P = 7.8 and AFBMA computed L_{10} life = 480×10^6 revs.) with Esso Turbo Oil 35, a highly viscous ester base oil, as the lubricant. The bore recessed cages assembled with the bearings were manufactured from either age hardened (Rc 33) S-Monel (Enclosure 4) or silver-plated hardened (Rc 55) M-1 steel (Enclosure 16). Both the inner and outer races of these bearings were black oxide coated for improved resistance to surface distress and the inner race ball grooves were specially ground and honed to improve their surface finish as a means of reducing lubrication distress in the bearings. A table of the results obtained to date, arranged in the order of increasing life, appears in Enclosure 17 and the bearing dimensions before test are given in Enclosure 7.

Only two of the six bearings tested so far in this group with silver-plated hardened (Rc 55) M-1 steel cages showed any appreciable cage wear (0.1 and 0.5 mils on the cage guide bore, respectively). Six of the ten aged (Rc 33) S-Monel cages tested in endurance bearings were 0.2 mils or greater on the cage bore, two of these in excess of 0.5 mils (21.5 mils on one cage, No. 206, and 43.0 mils on the cage in No. 208 bearing in Test E-4, in which the oil flow was interrupted by a broken sight-flow glass). These results indicate the superior performance of the silver-plated steel cages over the S-Monel cages, which have been found in recent Phase I tests to wear less than unplated hardened M-1 cages, as discussed above.

For the purpose of preparing the maximum likelihood life analyses of the bearings, as described in (3), the endurance results will be processed according to the following rules:

1. A bearing will be considered failed if any of its elements (except, of course, the cage) suffer fatigue flaking.
2. Both bearings in a test assembly will be started on test now, at the same time. In the event both bearings fail, one will be considered a failed bearing and the other, an induced failure, and thus will be treated as a suspension.
3. Should only one of two bearings fail in a test, the un-failed bearing will be considered a suspended test. It will not be run further.
4. If only the cage of a bearing fails (e.g. excessive bore wear, cracked cage pockets), the cage will be replaced and the test continued.
5. If cage failure and bearing fatigue failure exist in the same bearing so that it can be assumed that the cage failure has contributed to the premature failure of another element, then the fatigue failure will be considered an induced failure and treated as a suspended test.
6. Surface distress will not be considered a failure if the bearing can be run further. If, however, surface damage is so severe that the bearing cannot be run further, this mode of failure will be treated the same as a fatigue failure.

7. The existence of surface distress along with a fatigue failure in a bearing will be noted but not considered a reason for designating the failure as an induced one. Such failures will be considered legitimate in calculating life because surface distress is a consequence of the test conditions and may be unavoidable.

It is recognized that the exclusion rules 2, 4 and 5 tend to bias resultant life estimates towards longer life. Still, it is felt that these rules must be used in order that operational malfunctioning of the test be kept from derating the inherent endurance capabilities of the bearing-lubricant combination.

It is planned to run the bearings until failure or their time-up life of 90 hours (231.1×10^6 revs.).

Discussion of Phase II Test Results

As shown in Enclosure 17, sixteen bearings (eight tests) have run thus far without legitimate fatigue failures. In three tests, viz., E-1, E-2 and E-5, all six bearings reached their time-up life of 90 hours (231.1×10^6 revs.) without failure or lubrication distress. Two of the remaining five tests, viz., E-3 and E-8, were suspended because of excessive cage bore and inner race land wear in one of the two companion bearings being tested. Two additional tests (E-6, E-7) showed lubrication related surface damage and are considered legitimate failures. In each test, one of the two bearings was in good condition without surface distress. Only one test, E-4, was terminated early (after 3.0 hours (7.7×10^6 revs.)) due to excessive oil leakage from the drive end bearing sight glass which had cracked and eventually shattered. Examination of the bearings at this point indicated that the drive end bearing had glazed and worn heavily in its inner race land and in its cage bore, whereas the companion bearing was in OK condition. This test is considered a suspension.

Since this last test could not be considered a fair indication of the bearings' endurance, a Weibull plot of the endurance results excluding this test was prepared and is given in Enclosure 18. A maximum likelihood estimate of the bearing life is not shown on this enclosure. Based on the two legitimate failures, such an estimate will be given in the next report. From the Weibull plot of the bearings in this group, it already appears that their fatigue life is relatively good (no fatigue flaking to at least $1/5$ of the AFBMA computed L_{10} life).

The overall reliability of bearings operating under the severe test conditions of this program, considering all types of bearing failures, is obtained by considering all test bearings which suffer fatigue flaking, lubrication distress or cage wear as failures (some of these failures are normally excluded by rules 2, 4 or 5). A Weibull plot of the test results treated in this way is shown in Enclosure 19 and a preliminary maximum likelihood estimate of L_{10} life based on these few failures is $L_{10} = 129.7 \times 10^6$ revolutions. This estimated L_{10} is 27% of the AFBMA computed L_{10} life, which corresponds to a reduction of the basic dynamic capacity to 65% of that computed using AFBMA formulae and suggests that the bearings are definitely serviceable under these operating conditions. Of course, the number of failures to date is so small that no quantitative conclusion of any generality should be drawn regarding bearing endurance.

Should all thirty bearings in the group operate without a true fatigue failure occurring, then another group of CVM M-1 steel bearings will be tested next, under identical conditions except at a higher thrust load in order to obtain data on the inherent endurance capabilities of this bearing-lubricant combination.

4. Flat Washer Cage Material Screening Tests

In order to determine if a suspension of MoS_2 in a lubricant would permit it to lubricate at a higher temperature, three tests were conducted with two of the best wear resistant cage materials to date, M-1 (Rc 60) steel and S-Monel (Rc 33), at 1200 rpm, 1000 lbs. load and 700°F in the modified flat washer machine. A description of the test machine and the cage configuration is given in (4). The mechanism by which the wear scar is produced and a description of its measurement is given in (5). One previously tested lubricant, Esso FN-3157, and a highly viscous hydrocarbon, Kendex Bright Stock 0846, were each used to produce a suspension of 2% (by weight) of MoS_2 in the test oils. A third test was conducted with Kendex Bright Stock 0846 without the MoS_2 in suspension, as a base line. The MoS_2 used was Molykote Z (MIL-M-7866A), as manufactured by the Alpha Molykote Corporation and it has the following properties:

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<u>Particle Size (Microns)</u>	<u>% by Weight</u>	<u>% by No. of Particles</u>
10-20	-	.002
5-10	20	0.1
2-5	47	3.8
2	33	96.0

Evaluation of the performance of each lubricant was based on measurements of the average wear scar size obtained at half-hour intervals during the tests. A comparison of the wear scars was made for the oil as received and after addition of the MoS₂.

A summary of the results obtained in the tests is given in Enclosure 20. Curves of the wear scar area growth during each test are shown in Enclosures 21 and 22.

Discussion of Cage Material Screening Results

It is recalled that earlier tests had been run at 500°F and 700°F with a M-1 (Rc 60) cage specimen and Esso FN-3157 oil which did not contain MoS₂. The curves of wear scar area growth for this test are shown in Enclosure 28 of (1) and Enclosure 39 of (2), and are repeated in Enclosure 21 of this report. Based on a comparison of the initial wear scar areas and of their subsequent growth, the addition of the MoS₂ to the oil appears to have a detrimental effect on its performance with M-1 (Rc 60) cage material.

Since no previous cage material test had been conducted with the Kendex Bright Stock 0846 oil, a base line test was run with a S-Monel (Rc 33) cage specimen and this oil at 700°F. Another test was conducted with the same cage material using oil having 2% (by weight) MoS₂ added to form a suspension. The wear scar area growth produced in the two tests is shown in Enclosure 22, which indicates that no significant improvement was obtained by addition of MoS₂ to the oil.

Examination of the oil (with MoS₂ added) after each test revealed that a heavy sludge like deposit had formed during the test*. In view of the lack of improvement in the cage material

* It is believed that this deposit could have consisted of MoS₂ enriched oil (the MoS₂ was merely stirred into the oil before the test but not homogenized).

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<u>Particle Size (Microns)</u>	<u>% by Weight</u>	<u>% by No. of Particles</u>
10-20	-	.002
5-10	20	0.1
2-5	47	3.8
2	33	96.0

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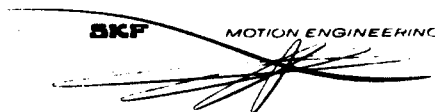
* It is believed that this deposit could have consisted of MoS₂ enriched oil (the MoS₂ was merely stirred into the oil before the test but not homogenized).

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performance with the oils containing MoS₂ and the sludging of these oils, it does not appear that an improvement in the high-temperature lubricating capabilities of the candidate high-temperature lubricants would be realized by addition of MoS₂. Therefore, Phase I type tests on the 7205 size bearing with oil containing MoS₂ will not be run.

LIST OF REFERENCES

1. Wachendorfer, C. J., "Bearing Lubricant Endurance Characteristics at High Speeds and High Temperatures", Progress Report No. 8, NASA Contract NASw-492.
2. Wachendorfer, C. J., "Bearing Lubricant Endurance Characteristics at High Speeds and High Temperatures", Progress Report No. 5, NASA Contract NASw-492.
3. Wachendorfer, C.J., "Bearing Lubricant Endurance Characteristics at High Speeds and High Temperatures", Progress Report No. 6, NASA Contract NASw-492.
4. Wachendorfer, C. J., "Bearing Lubricant Endurance Characteristics at High Speeds and High Temperatures", Progress Report No. 1, NASA Contract NASw-492.
5. Wachendorfer, C. J., "Bearing Lubricant Endurance Characteristics at High Speeds and High Temperatures", Progress Report No. 7, NASA Contract NASw-492.

APPENDIX**SKF INDUSTRIES, INC.**

ENGINEERING AND RESEARCH CENTER

BALL AND ROLLER BEARINGS

December 21, 1964

National Aeronautics and Space Administration
Lewis Research Center
21000 Brookpark Road
Cleveland 35, Ohio

Attn: Mr. W. J. Anderson

Re: Redirection of Contract No. NASw-492 "A Basic Study
of Bearing-Lubricant Endurance Characteristics at
High Speed and Temperatures"

Gentlemen:

Since my letter to you dated September 2, 1964, regarding the redirection of the above program, and as I have discussed with you by telephone, it has recently become necessary to further redirect the program in order to complete by September, 1965, the number of endurance groups originally planned. As outlined in my earlier letter, it was planned to spend the remaining time and funds both on continued Phase I screening of candidate lubricants and bearing materials utilizing one of the four test machines and on Phase II endurance tests utilizing the remaining three machines. The endurance groups planned were as follows:

- a) WB49 bearings at 600°F with Socony Mobil XRM 109F highly refined mineral oil.
- b) WB49 bearings at 500°F with Esso Turbo 35 ester-base oil.
- c) WB49 bearings at 600°F with Socony Mobil XRM 109F highly refined mineral oil at a higher load than that used in the previous groups (C/P = 7.8) to establish the load-life relationship at this temperature.
- d) M-1 bearings at 600°F with Socony Mobil XRM 109F highly refined mineral oil.
- e) 440C (modified) bearings at 600°F with Socony Mobil XRM 109F highly refined mineral oil.

f) If available machine time permits, a group of WB49 bearings run at 600°F with a modified Monsanto OS-124 polyphenyl ether oil according to a user's proprietary specification (Skylube 600).

The Socony Mobil Oil Company has now advised us that their XRM 109F oil will not be available in sufficient quantity to conduct endurance tests until early February, 1965. In addition, we have decided to press the development of the same type of superior groove finishing techniques now available for the M-1 bearings in use on this program for the WB49 and the 440C (modified) bearings manufactured for these endurance tests. This development has delayed the completion of the WB49 and the 440C (modified) bearings, now estimated to be available by the end of February, 1965. (M-1 test bearings with the superior finish are on hand). We believe that it is desirable to wait for these high surface finish tool steel and stainless steel bearings, in the light of our earlier Phase I results that indicated an important effect of the film thickness to surface roughness ratio on the tendency of high-temperature oils to produce surface distress and reduced life of bearings.

In order to overcome these delays and to complete the number of endurance groups originally planned, it is now proposed that the redirected Phase II tests be conducted in the following order:

a) M-1 bearings at 500°F with Esso Turbo 35 ester-base oil. This group has already been started and no fatigue failures have been experienced in seven tests.

b) If no failures are experienced in (a) then a repeat of (a) at higher loads to produce fatigue.

c) M-1 bearings at 600°F with a modified Monsanto OS-124 polyphenyl ether oil according to a user's proprietary specification. (Skylube 600)

d) M-1 bearings at 600°F with Socony Mobil XRM 109F highly refined mineral oil. (This oil will be available by the time we are ready to start this group.)

e) WB49 bearings at 600°F with Socony Mobil XRM 109F highly refined mineral oil.

f) 440C (modified) bearings at 600°F with Socony Mobil XRM 109F highly refined mineral oil, if available machine time permits.

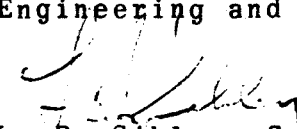
g) If time permits and if enough failures are obtained in group (a), then either M-1 or WB49 bearings (whichever gives longer life in groups (d) and (e) with Socony Mobil XRM 109F highly refined mineral oil at a lower load in order to obtain a load-life relationship.

We have found in our current Phase II testing at 42,800 rpm (the most satisfactory speed evolved for the three constant-speed machines) that cage wear and failure is more pronounced under these severe conditions than previously experienced in the Phase I testing at 20,000 rpm. Therefore, we have added to our continued Phase I testing (outlined in my letter of September 2, 1964) a few comparative tests of new candidate cage materials in these 7205 bearings at high-speed, such as, silver-plated M-1 steel and an S-Monel sprayed coating on M-1 steel. If any of these new cage materials have superior performance to those now being used in Phase II endurance bearings, the improved material will be substituted for the remainder of the Phase II testing.

We would appreciate having your approval of these proposed modifications of our redirected program. Should you have any questions concerning this redirection, please contact me.

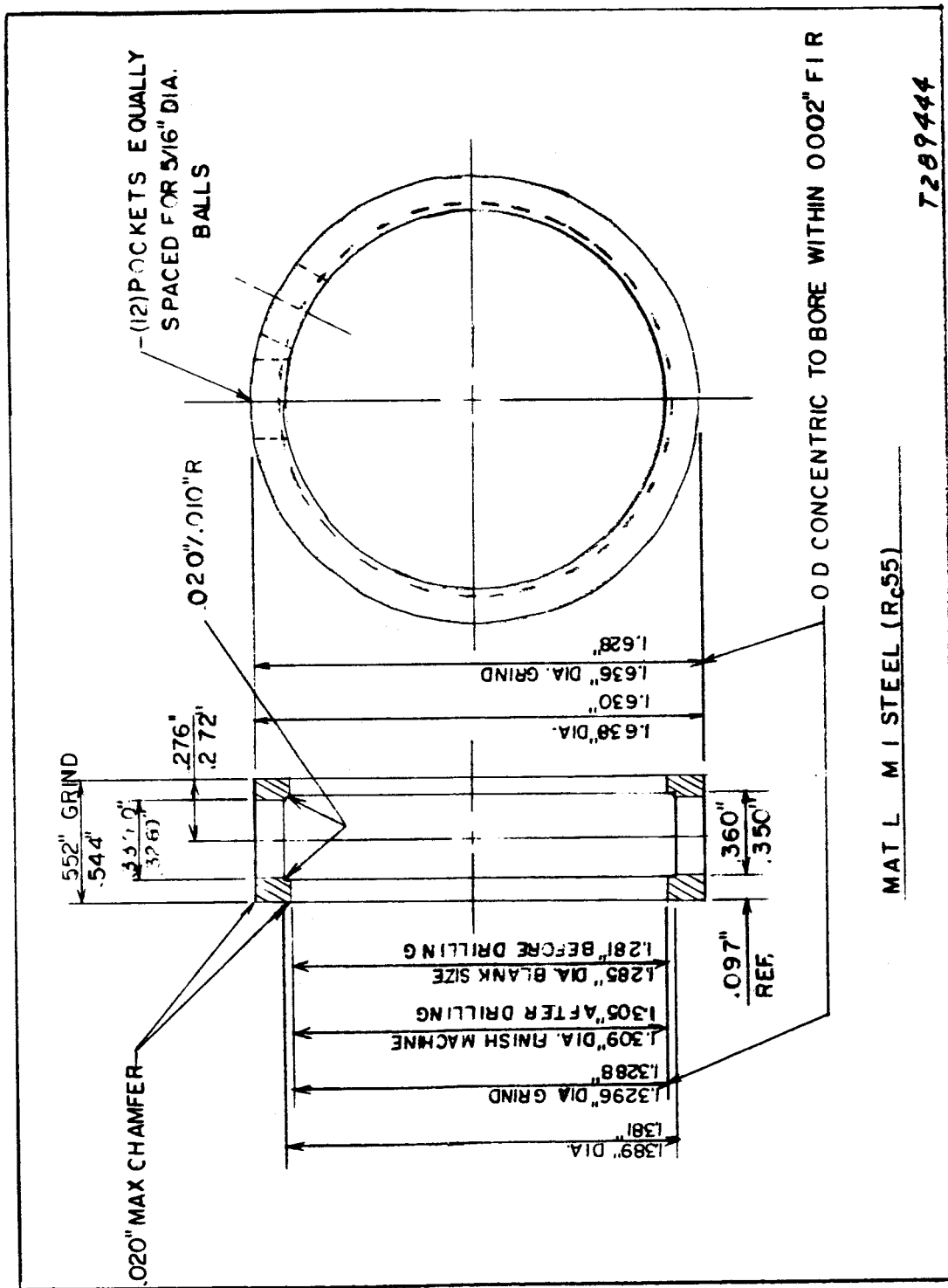
Very truly yours,

SKF Industries, Inc.
Engineering and Research Center

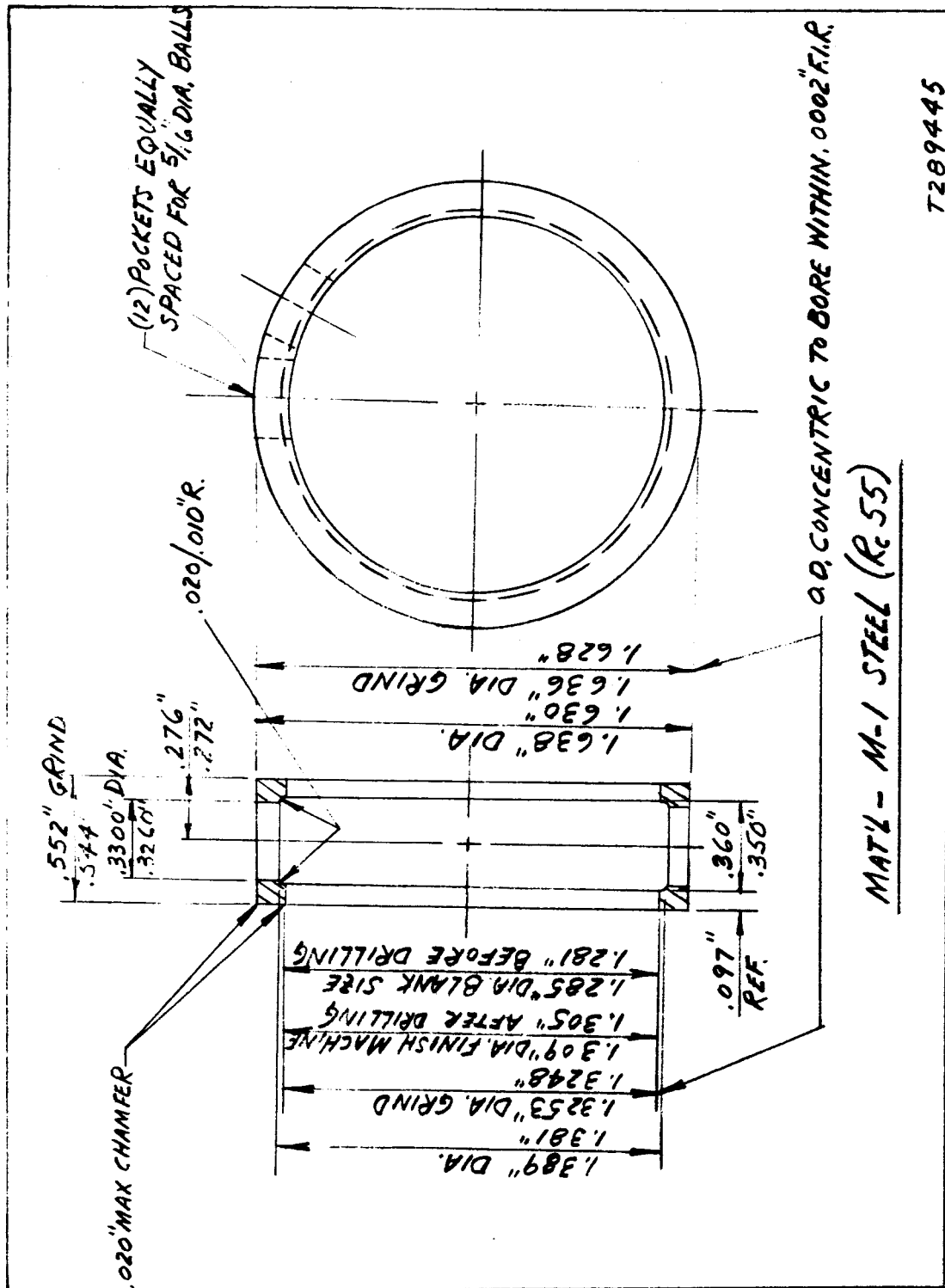

L. B. Sibley, Supervisor
Mechanical Test Section

LBS/rz

cc: Mr. M. Comberiate

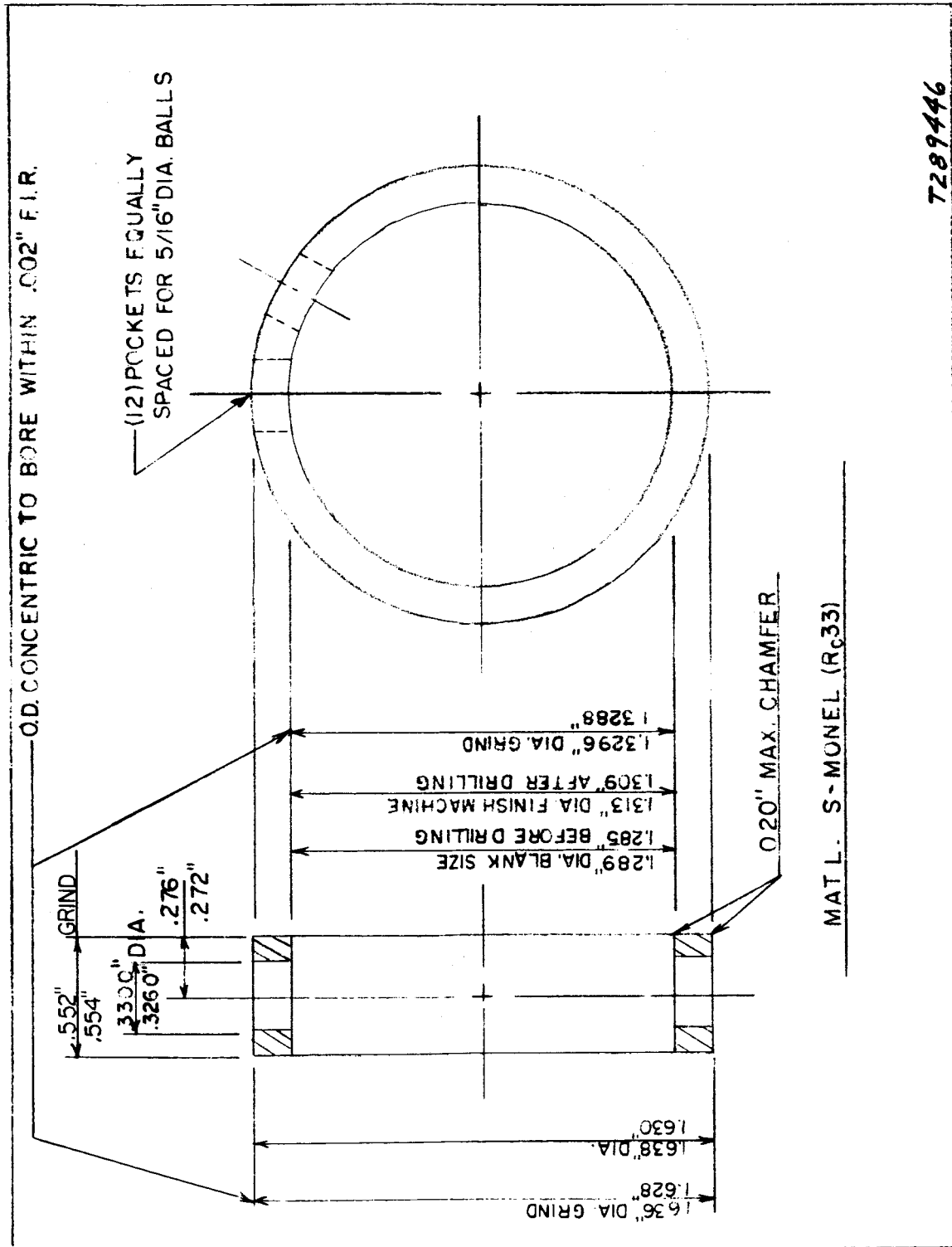


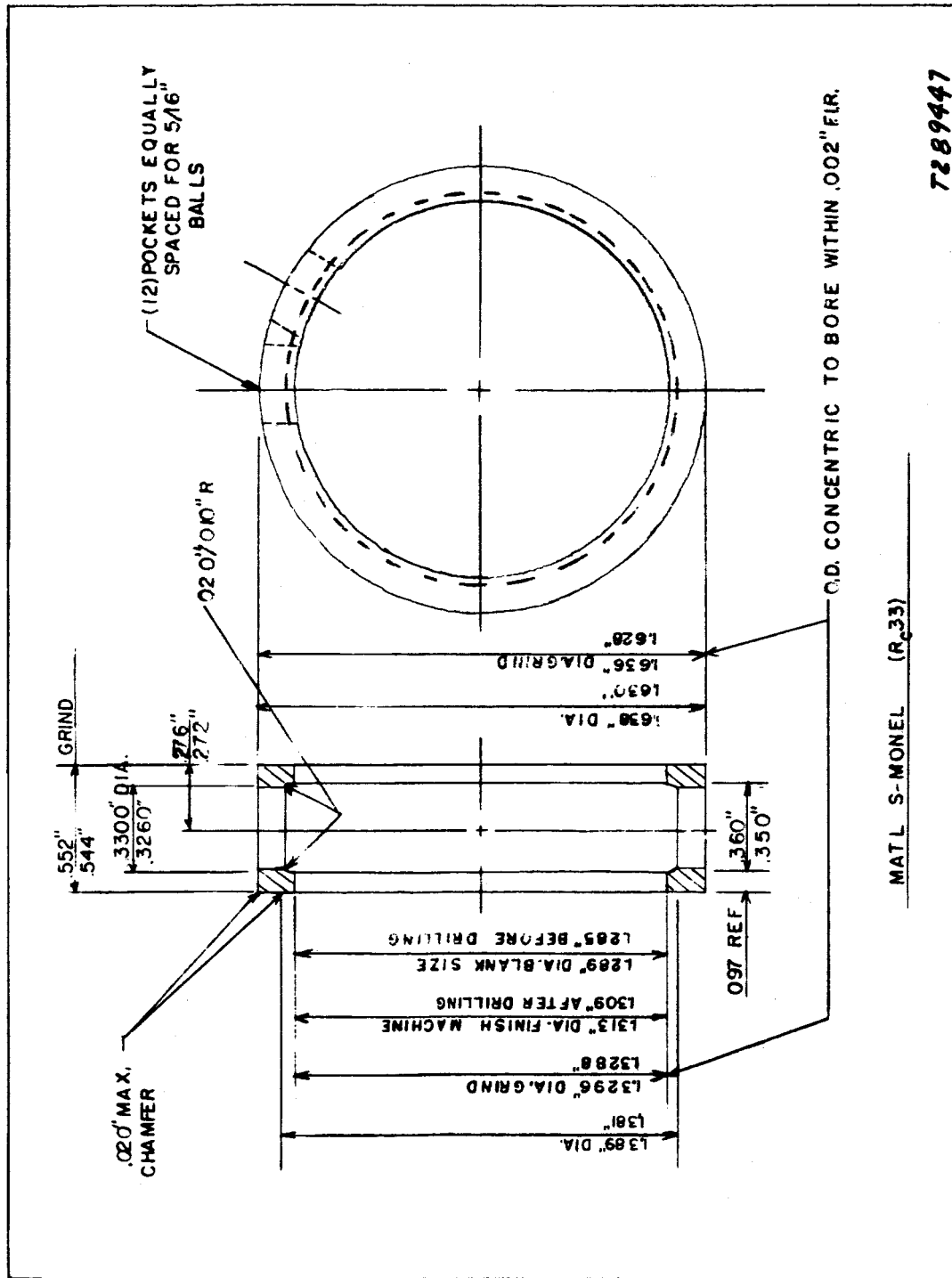
ENCLOSURE 2



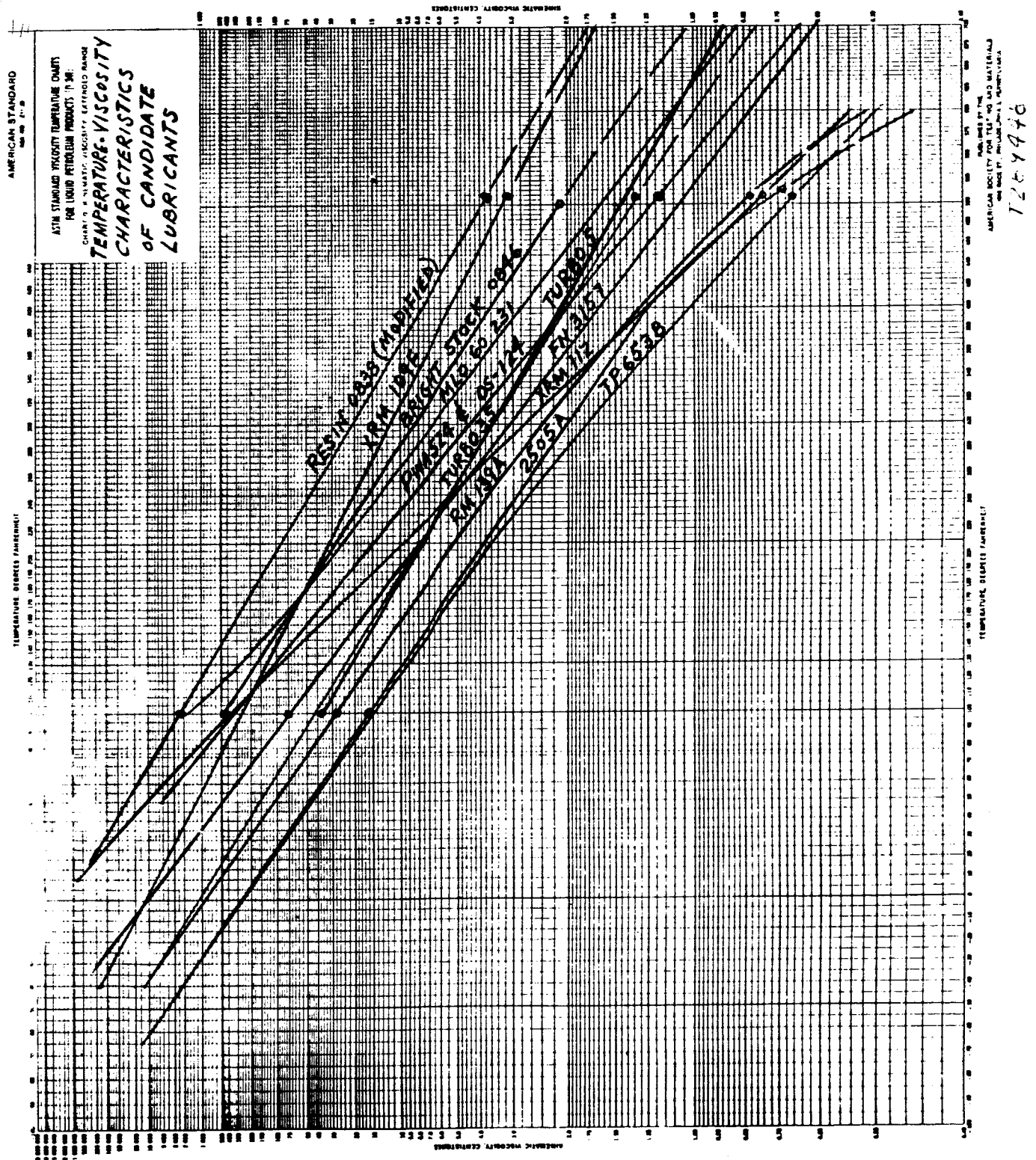
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ENCLOSURE 3





ENCLOSURE 5



ENCLOSURE 6

SUMMARIZED RESULTS OF PHASE I TESTING OF 7205 CVM M-1 STEEL BEARINGS (#455760)

RUN NO.	TEST BEARING		INITIAL RADIAL LOOSENESS (MICRONS)	TEST DURATION		SPEED 10 ³ RPM	THRUST LOAD LBS.	MEAN TEMPERATURE OF			OIL IN CONSUMED ML	OIL AFTER TEST		(G) BEARING CONDITION AFTER TEST	
	NO.	LOCATION		HOURS	10 ⁶ REVS.			LUB.	BEARING	HOUSING		OIL IN SUMP	Visc. AT 100°F		ACID NO.
52 (A) (B) (C)	163	DRIVE	46	1.9	3.9	42.8		540	517	577				SLIGHT 1.6	I.R. - FLAKED - LANDS GROOVED FROM CAGE O.P. - GLAZED BALLS - GOOD
	161	LOAD	49	0.7	1.8	42.8	365	618	543	580	41.6	0.39	7.8	NOT APPRECIABLE <0.1	I.R. & O.P. - SWEARED BALLS - SWEARED
	164		40	1.2	3.1	42.8		540	510	536				EXCESSIVE 24.2	I.R., O.P. & BALLS - SWEARED
53 (A) (D)	175	DRIVE	43	0.5 0.8	0.6 2.2	20 45	365	329 560	330 519	345 580		1916.5	0.06	<0.1	I.R. & O.P. - GOOD BALLS - GOOD
	174	LOAD	47	0.5 0.8	0.6 2.2	20 45		350 680	330 519	335 558				SLIGHT 2.5	I.R. & O.P. - GLAZED AND FLAKED BALLS - (11) GOOD - (1) FLAKED
54 (A) (E)	193	DRIVE	46	35.2	95.0	45	365	500	510	484	8850			VERY SLIGHT 0.5	I.R. - GOOD - O.P. - SLIGHTLY GLAZED BALLS - GOOD
	192	LOAD	46	35.2	95.0	45		550	510	510				VERY SLIGHT/ SLIGHT 0.4/ 3.0	I.R. - GLAZED & FLAKED (LANDS GROOVED FROM CAGE BORE WEAR) O.P. - GLAZED BALLS - GOOD
55 (A) (F)	197	DRIVE	45	90.0	243.0	45	365	525	500	505	4225	418.2	0.06	0.5	I.R. & O.P. - GOOD (SLIGHT FRAGMENT DENTING) BALLS - GOOD
	196	LOAD	52	90.0	243.0	45		550	500	475				VERY SLIGHT 1.0	I.R. & O.P. - GOOD (SLIGHT FRAGMENT DENTING) BALLS - GOOD

(A) THE BEARINGS WERE ASSEMBLED WITH HONED INNER RACES.

(B) THE BEARINGS WERE ASSEMBLED WITH BORE RECESSED M-1 (RC 55) CAGES HAVING A BORE CLEARANCE OF .006" - .008" (ENCLOSURE 1).

(C) BEARING #164 REPLACED BEARING #161 WHICH HAD SHEARED AFTER 0.7 HRS. (1.8 MILL. REVS.).

(D) THE BEARINGS WERE ASSEMBLED WITH BORE RECESSED M-1 (RC 55) CAGES HAVING A BORE CLEARANCE OF .002" - .003" (ENCLOSURE 2).

(E) BEARING #193 WAS ASSEMBLED WITH A STRAIGHT BORE S-MONEL (RC 33) CAGE HAVING A BORE CLEARANCE OF .006" - .008" (ENCLOSURE 3). BEARING #192 WAS INITIALLY ASSEMBLED WITH A STRAIGHT BORE S-MONEL (RC 33) CAGE HAVING A BORE CLEARANCE OF .006" - .008" (ENCLOSURE 3) WHICH WAS REPLACED BECAUSE OF CRACKED POCKETS AFTER 33 HRS. OPERATION WITH A BORE RECESSED M-1 (RC 55) CAGE HAVING A BORE CLEARANCE OF .006" - .008" (ENCLOSURE 1) AND THE CAGE BORE WEAR IS SO INDICATED FOR EACH CAGE.

(F) THE BEARINGS WERE ASSEMBLED WITH BORE RECESSED S-MONEL (RC 33) CAGES HAVING A BORE CLEARANCE OF .006" - .008" (ENCLOSURE 4).

(G) A BEARING IS CONSIDERED TO BE IN GOOD CONDITION IF AFTER TESTING THE FINISHING MARKS PRODUCED IN MANUFACTURING OF THE BEARING ARE STILL EVIDENT IN THE BALL PATH. A SLIGHTLY GLAZED BEARING IS ONE IN WHICH THESE FINISHING MARKS ARE NOT AS OUTSTANDING OR ARE PARTIALLY REMOVED.

THE UNUSED OILS HAVE THE FOLLOWING PROPERTIES

LUBRICANT	Visc. at 100°F CS	ACID NO.	SOLIDS MG/100 ML
SINCLAIR TURBO S	38.8	0.22	1.5
OS-139	1802.9	0.06	3.5
KEMDEX 0846	446.9	0.10	4.4

SKF 7205 ANGULAR CONTACT TEST BEARING DIMENSIONS BEFORE TEST

BEARING No.	AVERAGE OUTSIDE DIAMETER	AVERAGE BORE DIAMETER	CONTACT ANGLE DEGREES	AVERAGE RADIAL LOOSENESS (MICRONS)	AVERAGE RADIAL CAGE PLAY INCHES	TAPER MICRONS		OUT OF ROUNDNESS (MICRONS)	
						O.R.	I.R.	O.R.	I.R.
168	51.996	24.997	20.8	46	.0067	1.5	0.5	3.0	3.0
161	51.997	24.997	20.4	50	.0071	0.0	1.5	2.0	2.0
164	51.997	24.996	18.5	41	.0070	2.0	0.0	2.0	2.0
175	51.999	24.998	19.9	43	.0039	2.0	1.0	2.0	1.0
174	51.998	24.996	19.0	47	.0039	1.0	0.0	2.0	1.0
193	51.997	24.996	21.0	46	.0068	2.5	0.5	3.0	2.0
192	51.998	24.996	19.9	46	.0074	0.0	0.5	3.0	2.0
197	51.997	24.996	21.4	45	.0065	2.0	0.0	2.0	1.0
196	51.996	24.998	20.3	52	.0061	0.5	1.0	3.0	1.0
201	51.996	24.996	20.8	50	.0068	1.5	1.5	5.0	2.0
202	51.995	24.997	20.4	45	.0067	3.0	0.5	2.0	2.0
203	51.997	24.997	20.4	48	.0065	0.5	0.0	4.0	2.0
204	51.997	24.997	18.8	48	.0070	1.0	1.0	3.0	1.0
205	52.000	24.996	19.9	48	.0065	1.5	1.0	2.0	1.0
206	51.995	24.999	19.5	47	.0065	1.0	1.0	3.0	1.0
207	51.996	24.995	19.9	48	.007	2.5	0.0	3.0	1.0
208	51.999	24.996	19.0	49	.007	2.0	1.0	2.0	2.0
209	51.995	24.996	18.3	35	.0065	0.0	0.5	2.0	2.0
210	51.999	24.998	21.8	48	.0065	1.0	0.0	2.0	1.0
218	51.996	24.997	21.2	51	.007	5.0	1.0	2.0	1.0
214	51.996	24.996	20.4	51	.0065	1.5	0.0	3.0	1.0
218	51.996	24.997	21.7	52	.006	3.0	0.0	2.0	2.0
219	51.998	24.996	19.0	48	.0065	1.0	0.0	3.0	1.0
220	51.995	24.998	19.5	45	.0065	2.0	1.0	3.0	1.0
221	51.997	24.996	19.5	48	.0065	3.0	0.5	3.0	2.0

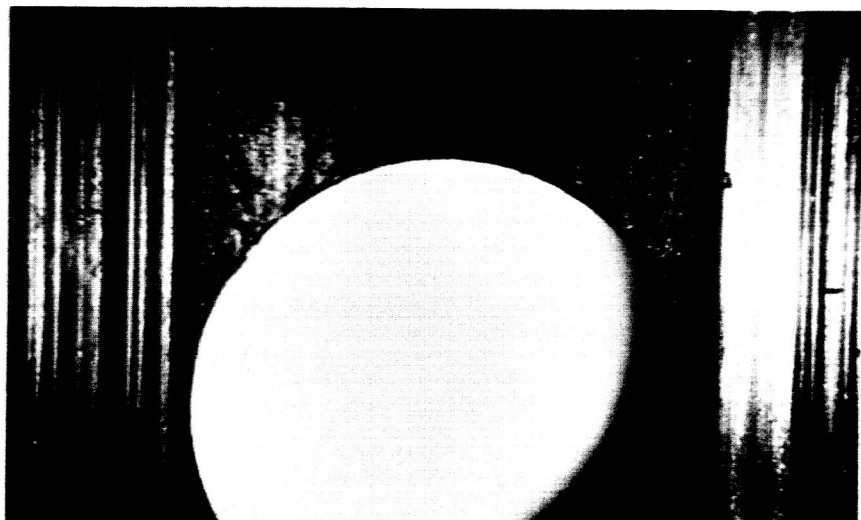
	MAXIMUM	MINIMUM
OUTSIDE DIAMETER (MM)	52.000	51.990
BORE DIAMETER (MM)	25.000	24.995
I.R. TAPER (MICRONS)	8	-
O.R. OUT OF ROUNDNESS (MICRONS)	5	-
I.R. OUT OF ROUNDNESS (MICRONS)	5	-
O.R. GROOVE CONFORMITY (%)	53.2	53.1
I.R. GROOVE CONFORMITY (%)	52.4	52.1
RADIAL LOOSENESS	50.0	40.0

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ENCLOSURE 8

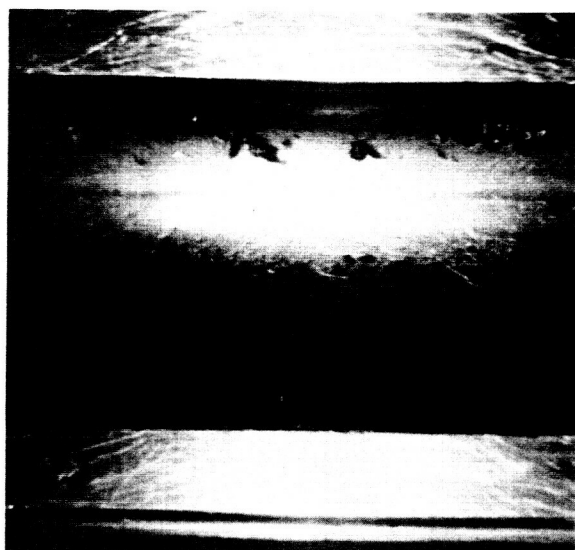
FAILED M-1 TOOL STEEL BEARING AFTER RUNNING 4.9×10^6 REVOLUTIONS AT 42,800 RPM, A MEAN TEMPERATURE OF 540°F AND UNDER 365 LBS. THRUST LOAD WITH CIRCULATING SINCLAIR TURBO S (TYPE 1048 IMPROVED) OIL IN A N₂ BLANKET

(Bearing No. 163 on Drive End from Run No. 52)



T289420

CAGE



INNER RACEWAY

T289409



OUTER RACEWAY

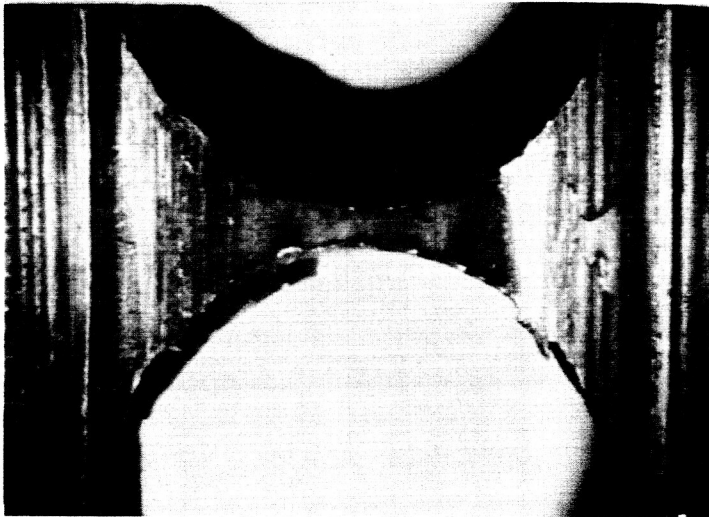
T289401

AL65T002

ENCLOSURE 9

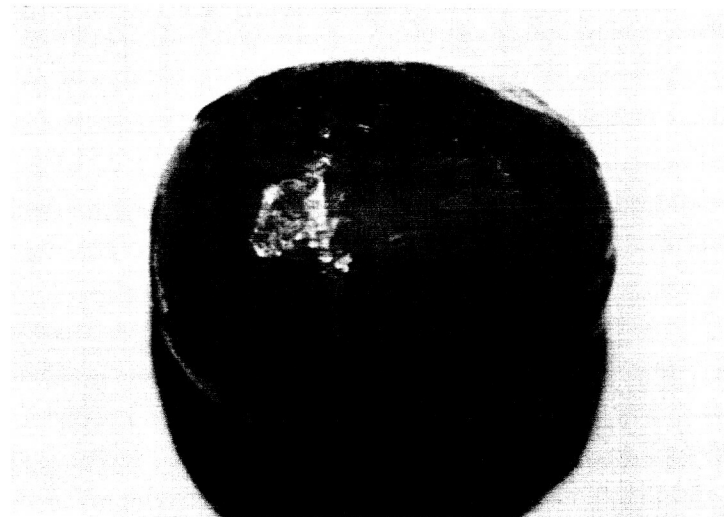
FAILED M-1 TOOL STEEL BEARING AFTER RUNNING 3.1×10^6 REVOLUTIONS
AT 42,800 RPM, A MEAN TEMPERATURE OF 540°F AND UNDER 365 LBS. THRUST
LOAD WITH CIRCULATING SINCLAIR TURBO S (TYPE 1048 IMPROVED) OIL IN A
N₂ BLANKET

(Bearing No. 164 on Load End From Run No. 52)



CAGE

T289424



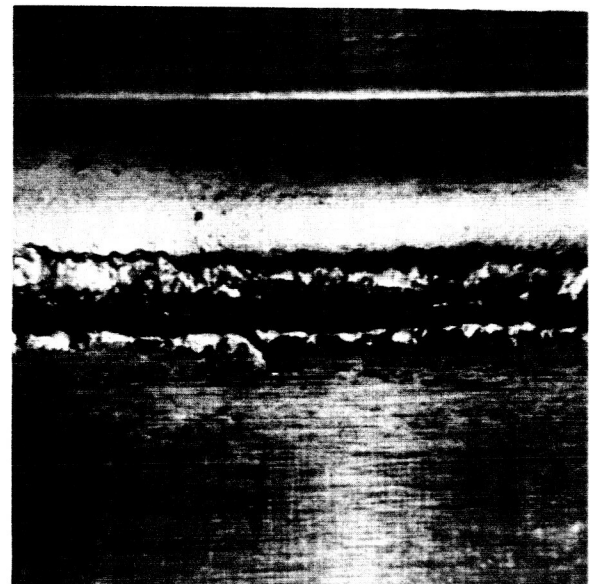
BALL

T289432



INNER RACEWAY

T289415



OUTER RACEWAY

T289404

AL65T002

ENCLOSURE 10

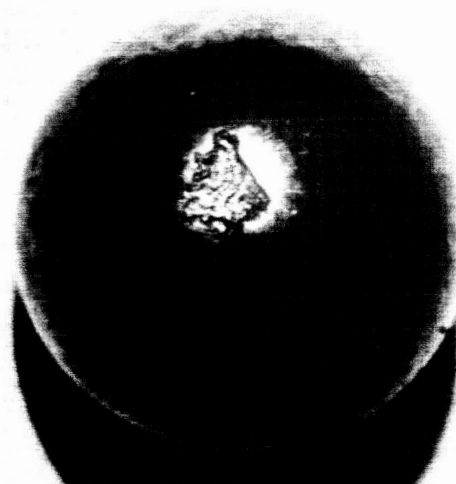
FAILED M-1 TOOL STEEL BEARING AFTER RUNNING 2.2×10^6 REVOLUTIONS
AT 45,000 RPM, A MEAN TEMPERATURE OF 680°F AND UNDER 365 LBS. THRUST
LOAD WITH CIRCULATING MONSANTO OS-138 OIL IN A N₂ BLANKET

(Bearing No. 174 on Load End From Run No. 53)



T289426

CAGE



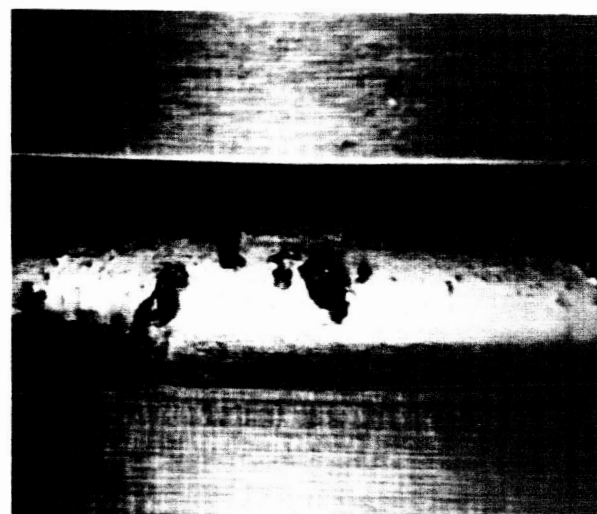
T289431

BALL



T289416

INNER RACEWAY



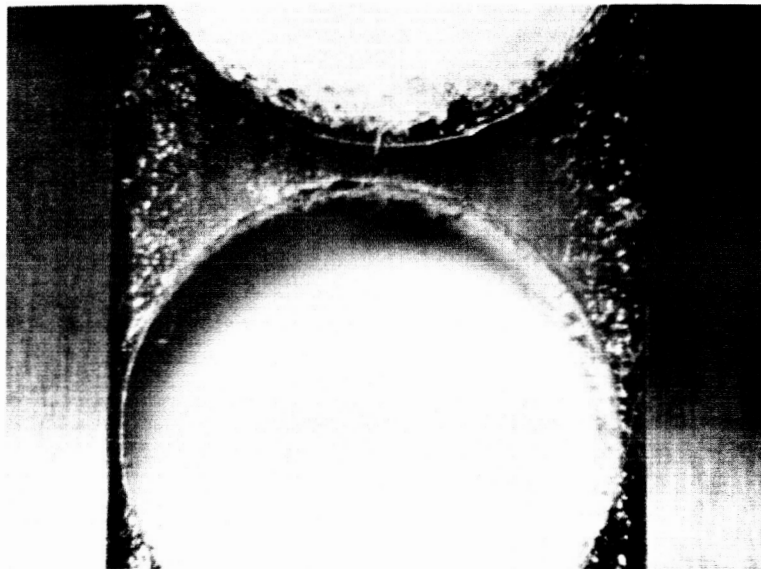
T289405

OUTER RACEWAY

ENCLOSURE 11

UNFAILED M-1 TOOL STEEL BEARING AFTER RUNNING 2.2×10^6 REVOLUTIONS
AT 45,000 RPM, A MEAN TEMPERATURE OF 560 °F AND UNDER 365 LBS. THRUST
LOAD WITH CIRCULATING MONSANTO OS-138 OIL IN A N₂ BLANKET.

(Bearing No. 175 on Drive End From Run No. 53)



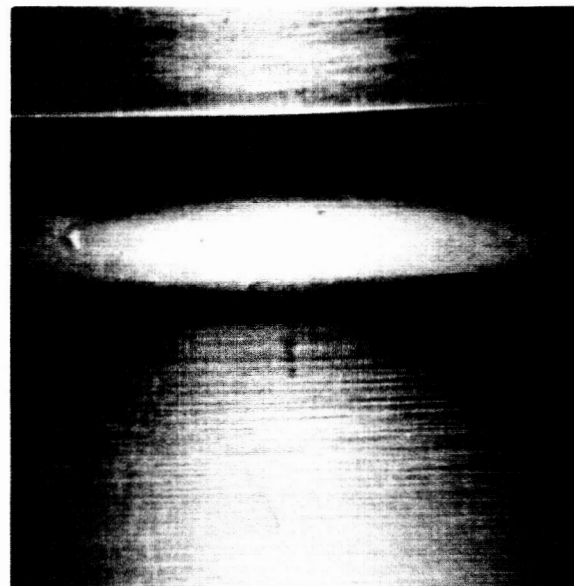
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CAGE



INNER RACEWAY

T289414



OUTER RACEWAY

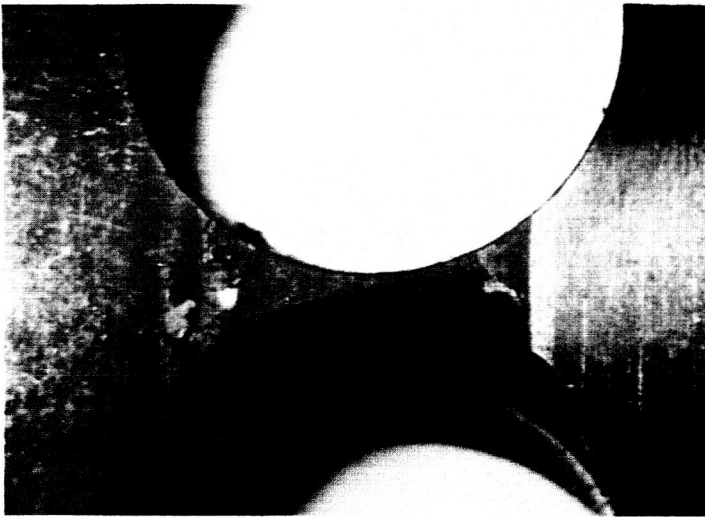
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ENCLOSURE 12

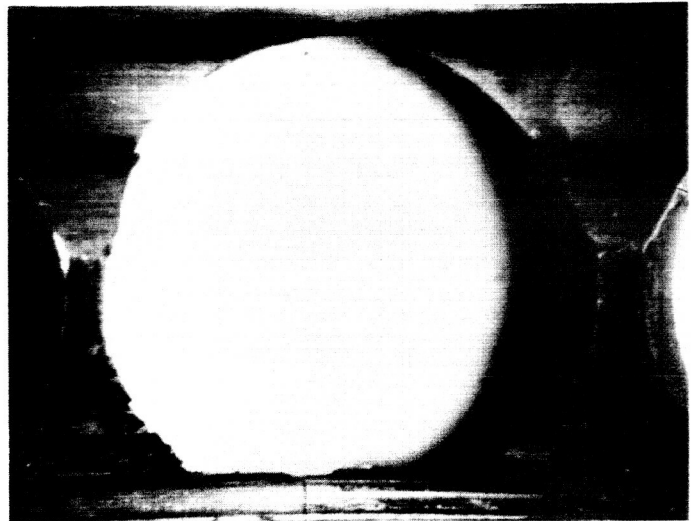
FAILED M-1 TOOL STEEL BEARING AFTER RUNNING 95×10^6 REVOLUTIONS
AT 45,000 RPM, A MEAN TEMPERATURE OF 550°F AND UNDER 365 LBS.
THRUST LOAD WITH CIRCULATING KENDEX BRIGHT STOCK 0846 OIL IN A
N₂ BLANKET

(Bearing No. 192 on Load End From Run No. 54)



INITIAL CAGE

T289422



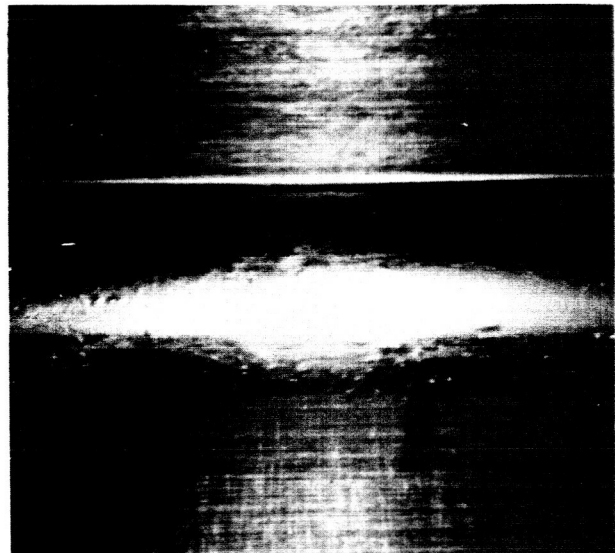
REPLACEMENT CAGE

T289428



INNER RACEWAY

T289412



OUTER RACEWAY

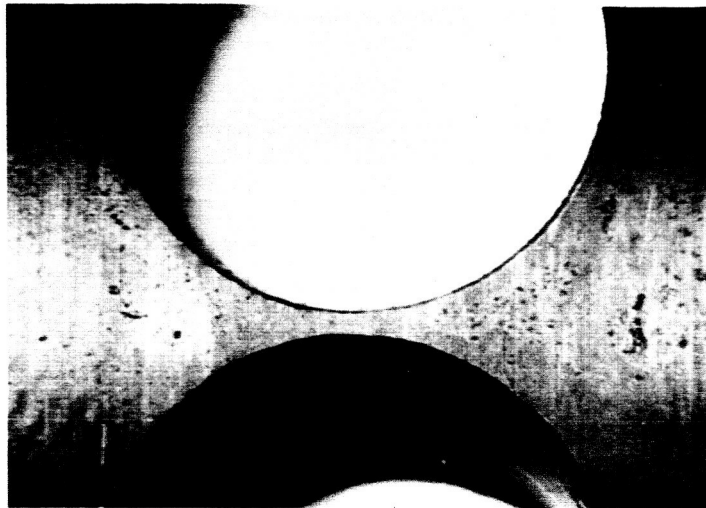
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ENCLOSURE 13

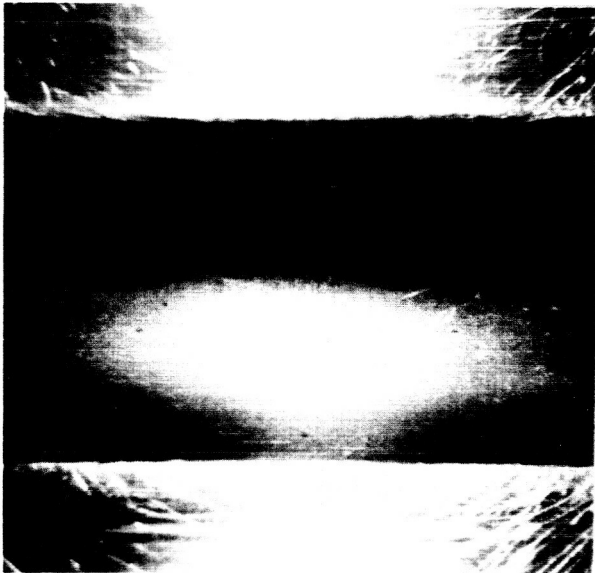
UNFAILED M-1 TOOL STEEL BEARING AFTER RUNNING 95×10^6 REVOLUTIONS
AT 45,000 RPM, A MEAN TEMPERATURE OF 500°F AND UNDER 365 LBS. THRUST
LOAD WITH CIRCULATING KENDEX BRIGHT STOCK 0846 OIL IN A N₂ BLANKET

(Bearing No. 193 on Drive End from Run No. 54)



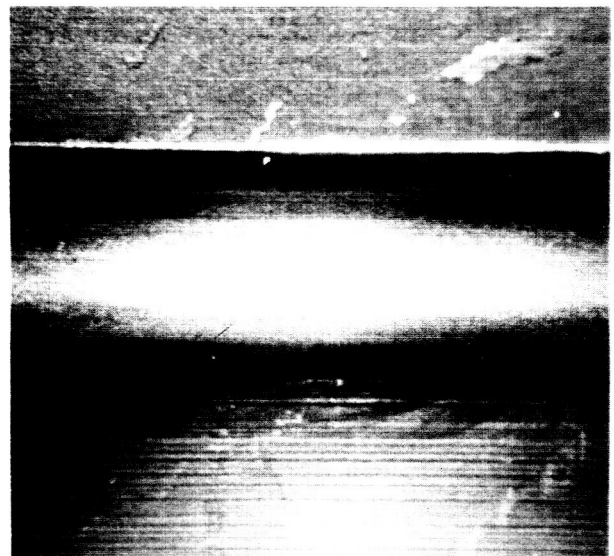
T289421

CAGE



INNER RACEWAY

T289411



OUTER RACEWAY

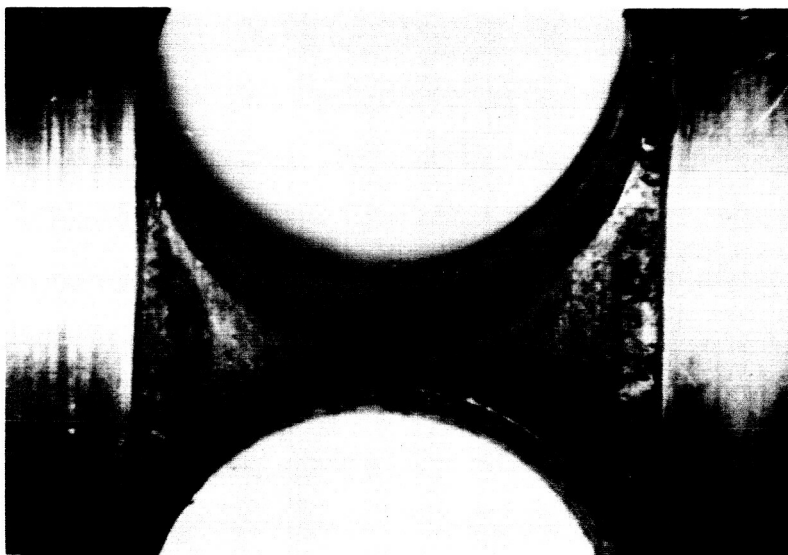
T289407

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ENCLOSURE 14

UNFAILED M-1 TOOL STEEL BEARING AFTER RUNNING 243×10^6 REVOLUTIONS
AT 45,000 RPM, A MEAN TEMPERATURE OF 525°F AND UNDER 365 LBS. THRUST
LOAD WITH CIRCULATING KENDEX BRIGHT STOCK 0846 OIL IN A N₂ BLANKET.

(Bearing No. 197 on Drive End From Run No. 55)



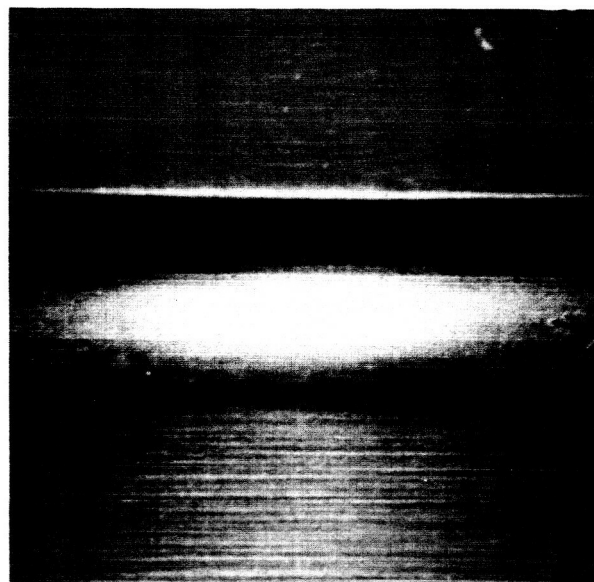
T289419

CAGE



T289410

INNER RACEWAY



T289400

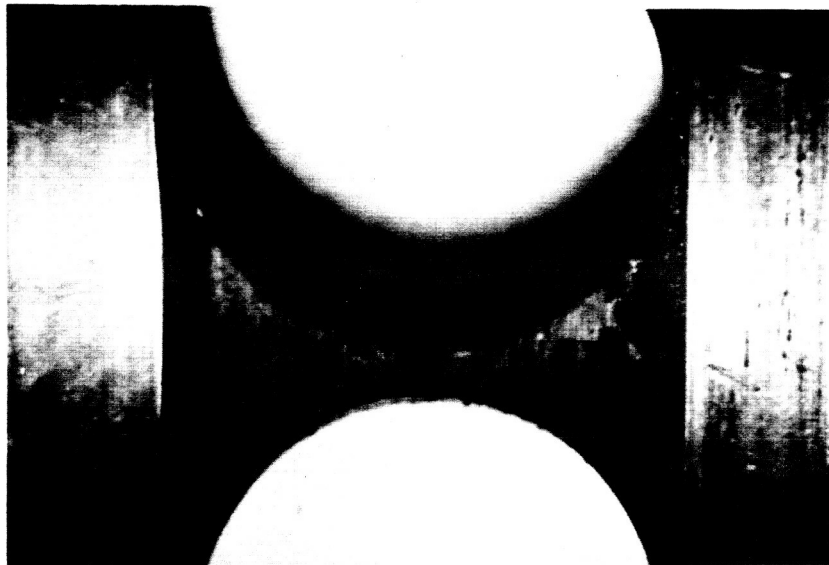
OUTER RACEWAY

AL65T002

ENCLOSURE 15

UNFAILED M-1 TOOL STEEL BEARING AFTER RUNNING 243×10^6 REVOLUTIONS
AT 45,000 RPM, A MEAN TEMPERATURE OF 550°F AND UNDER 365 LBS. THRUST
LOAD WITH CIRCULATING KENDEX BRIGHT STOCK 0846 OIL IN A N₂ BLANKET

(Bearing No. 196 on Load End From Run No. 55)

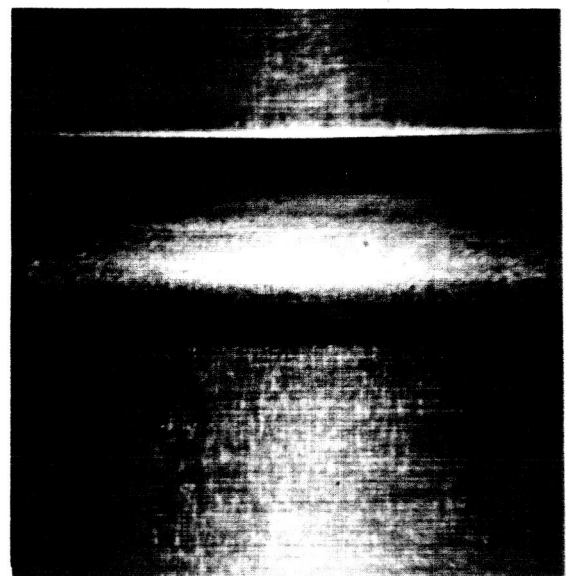


CAGE



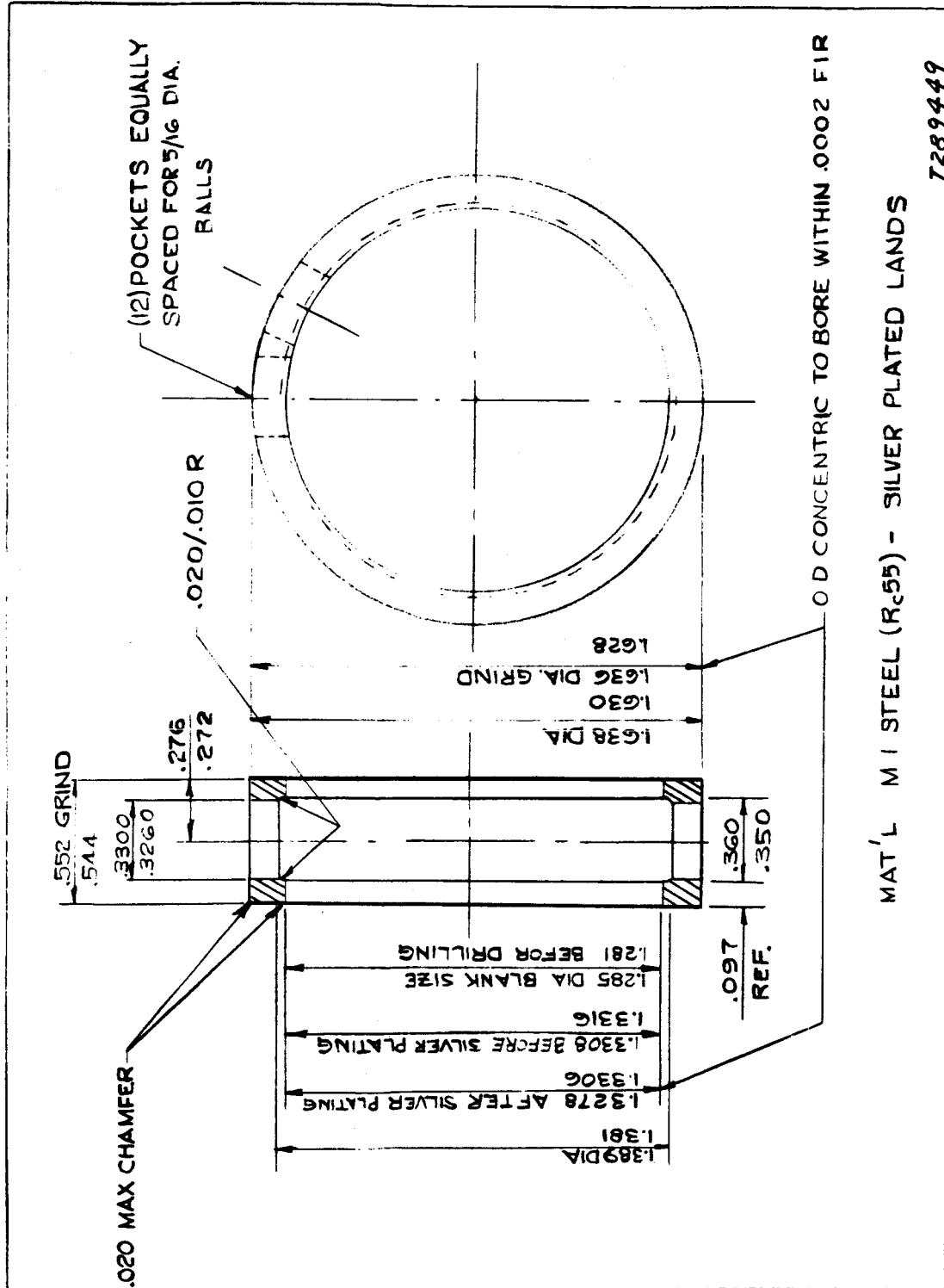
INNER RACEWAY

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OUTER RACEWAY

T289406



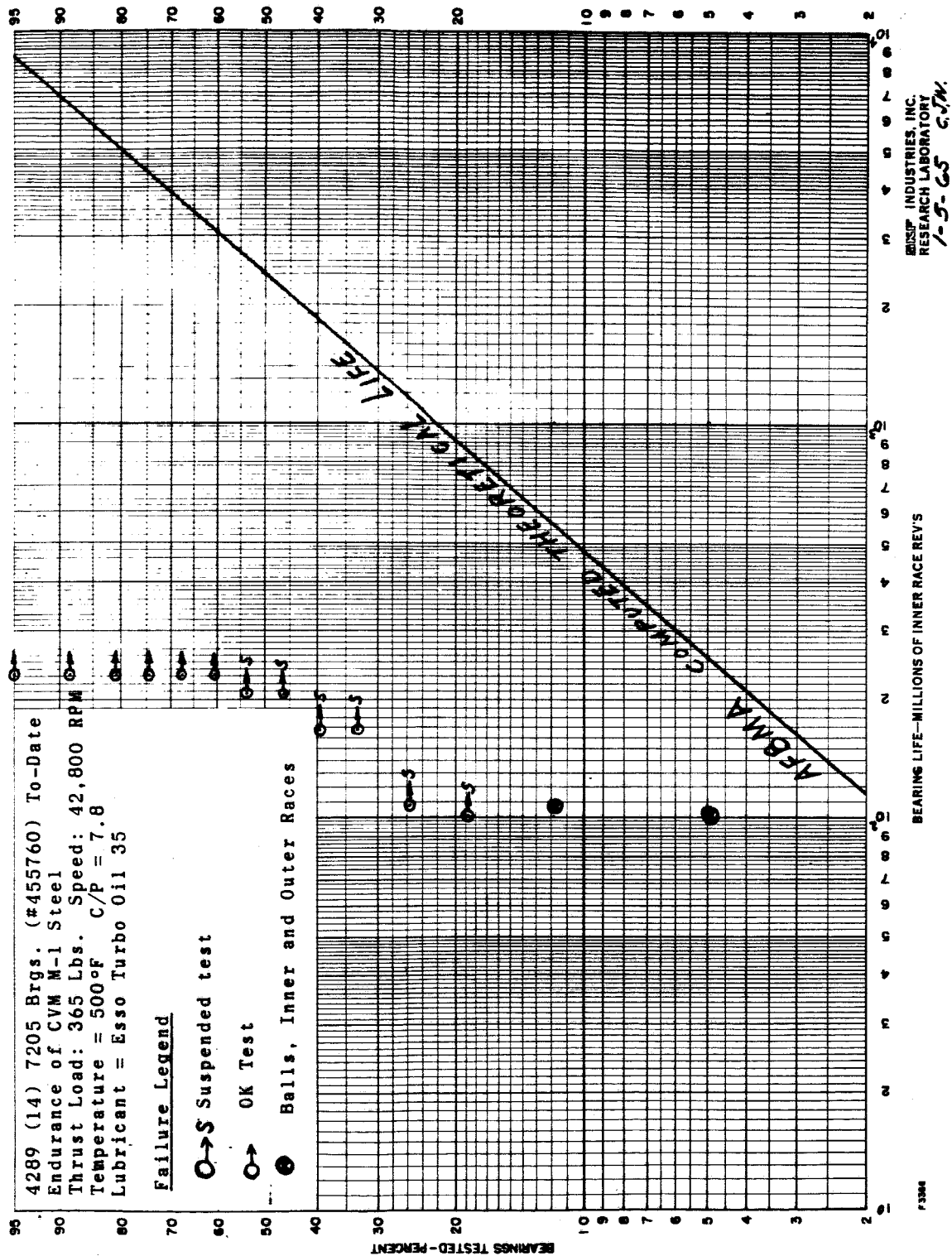
ENCLOSURE 17

ENDURANCE OF CVM M-1 7205 BEARINGS (#455760)

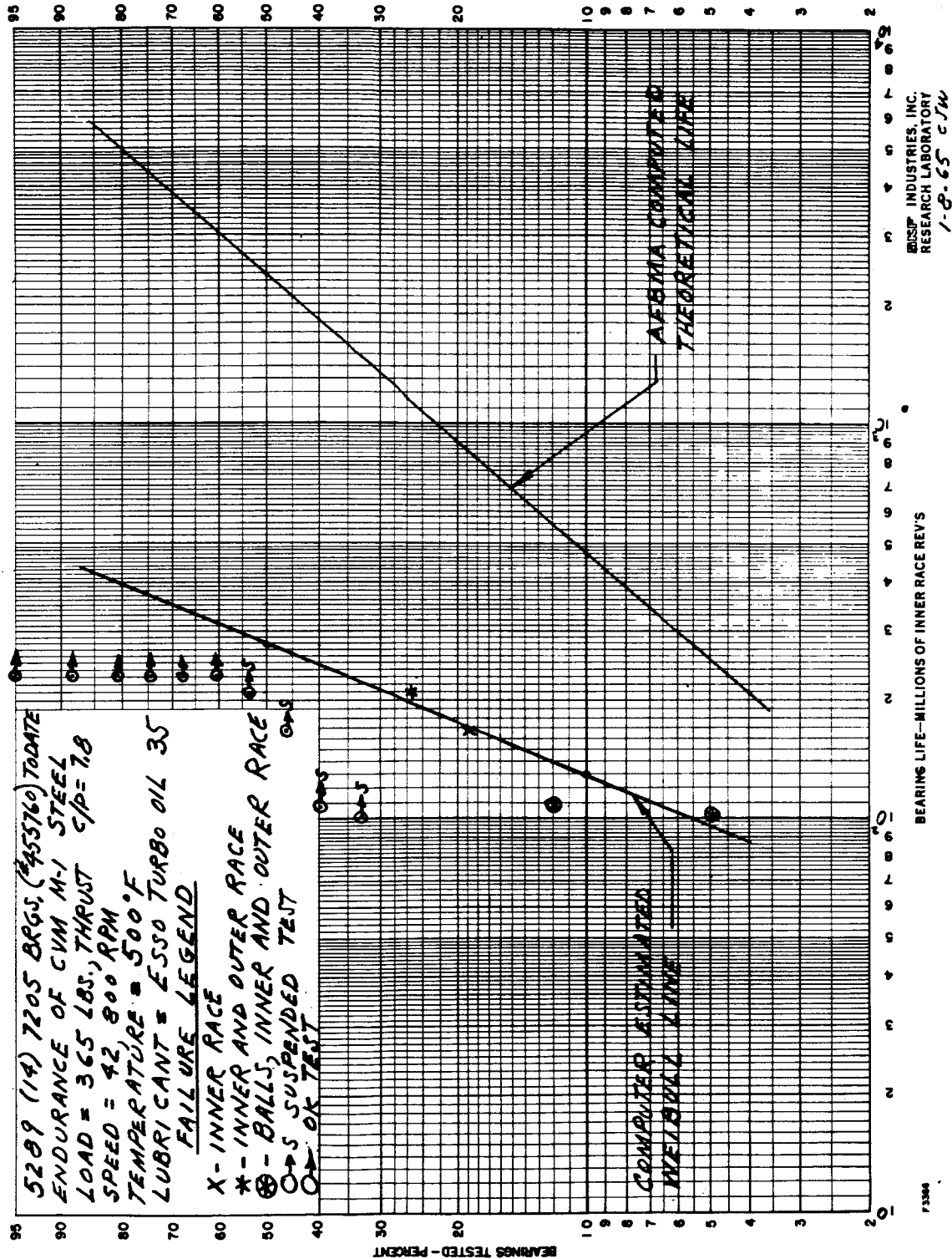
Thrust Load - 365 lbs.			Speed - 42,800 rpm		Lubricant - Esso Turbo Oil 35	
Test Run No.	Bearing No.	Cage Material	Avg. Temp. of F.	Lubrication Distress	Part Failed	Life, 10 ⁶ Revs.
E-4	207	S-Monel (Rc 33)	490	None	OK	7.7
	208	" "	473	Glazed	OK*	7.7
E-7	220	M-1 (Rc 55) Steel**	510	None	OK	101.2
	221	" "	490	Smeared	OR, IR, Balls	101.2
E-6	213	M-1 (Rc 55) Steel**	485	Smeared	OR, IR, Balls	108.1
	214	" "	510	None	OK	108.1
E-8	218	S-Monel (Rc 33)	505	Superficially Pitted	OK	168.5
	219	" "	500	None	OK	168.5
E-3	205	S-Monel (Rc 33)	496	None	OK	209.4
	206	" "	475	Slightly Glazed	OK*	209.4
E-1	201	S-Monel (Rc 33)	500	None	OK	231.1
	202	" "	485	None	OK	231.1
E-2	203	S-Monel (Rc 33)	505	None	OK	231.1
	204	" "	500	None	OK	231.1
E-5	209	S-Monel (Rc 33)	515	None	OK	231.1
	210	" "	492	None	OK	231.1

* The ball paths of both races were in OK condition, but inner race lands and cage bore had worn excessively. Therefore, the test was suspended.

**Silver-plated bore



ENCLOSURE 19



CAGE COMPATABILITY TEST RESULTS WITH HIGH TEMPERATURE LUBRICANTS
AT 1200 RPM AND 1000 LBS. LOAD

TEST NO.	CAGE MATERIAL	HARDNESS	LIQUID LUBRICANT	LUB. FLOW CU/MIN.	TEMP. OF	HOURS RUN	AVERAGE WEAR SCAR			N ₂ FLOW SCHEM S.C.F.H.	OIL ANALYSIS		
							MAJOR AXIS (IN)	MINOR AXIS (IN)	AREA (SQ IN)		DIRTY CONTENT MG/100 ML	VISC. @100°F	ACID NO.
69	M-1	Rc 60	24 MOS-2- FN 3157	5	700	0.5 1.5	4.4 6.4	2.1 3.2	7.3 16.1	2	-	-	-
71	S-MONEL	Rc 33	KENDEX BRIGHT STOCK 0846	2	700	0.5 2.0	1.8 2.0	0.7 0.8	0.9 1.3	2	74.4	576.2	.06
72	S-MONEL	Rc 33	24 MOS-2- KENDEX BRIGHT STOCK 0846	2.0	700	0.5 1.5	2.5 2.9	0.6 0.5	1.2 1.2	2	-	-	-

* STANDARD CUBIC FEET PER HOUR

THE UNUSED OILS HAVE THE FOLLOWING PROPERTIES

LUBRICANT	VISC. @ 100°F	ACID NO.	SOLID MG/100 ML
KENDEX 0846	446.9	0.10	4.4
Esso FN 3157	80.4	0.11	2.0

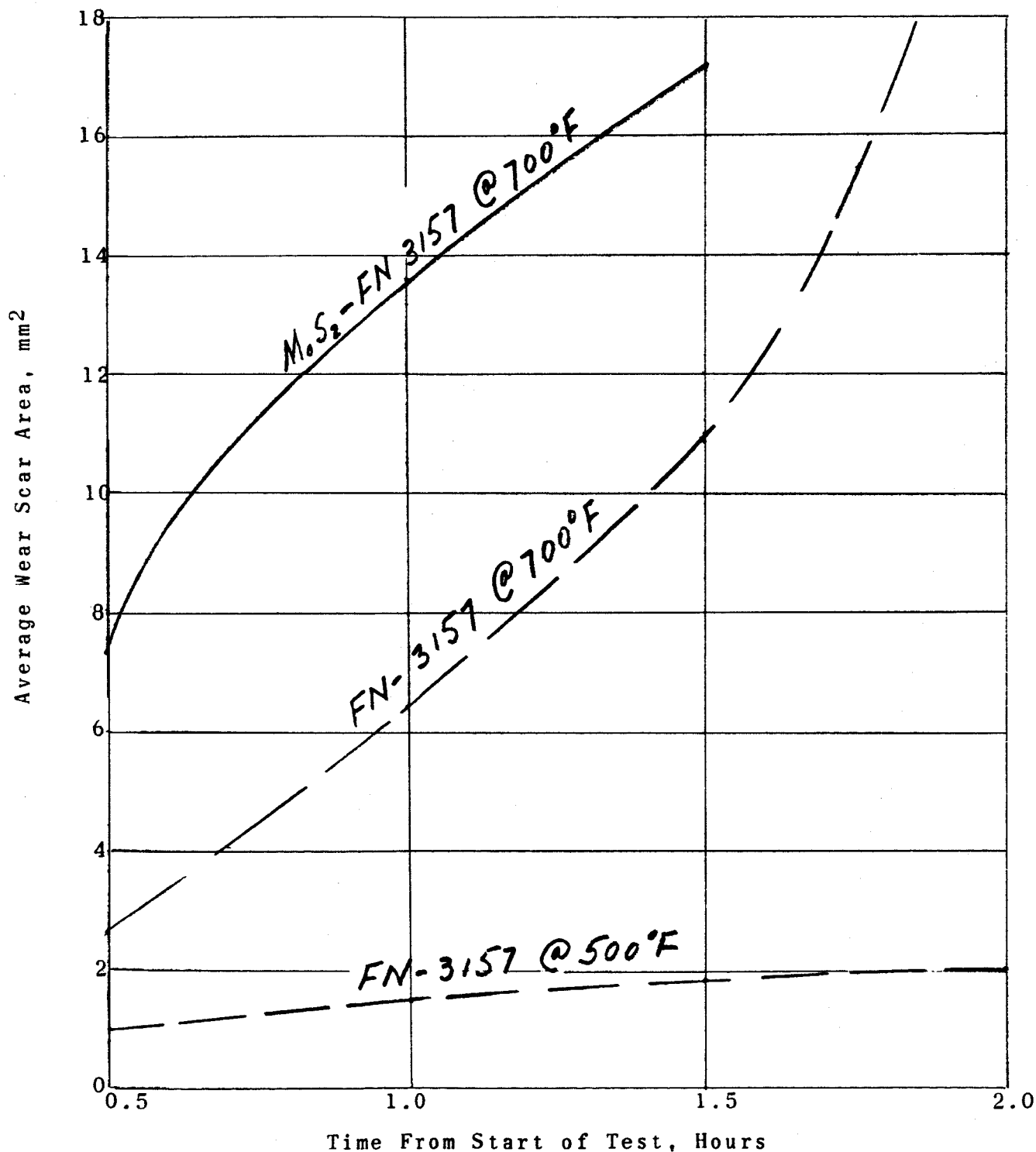
ENCLOSURE 20

AL65T002

ENCLOSURE 21

CAGE COMPATABILITY TEST RESULTS WITH M-1 (Rc 60) CAGE SPECIMENS
USING LUBRICANTS NOTED AT 1,000 LBS. LOAD AND 1200 RPM

(Average Wear Scar Area Vs. Hours Run)

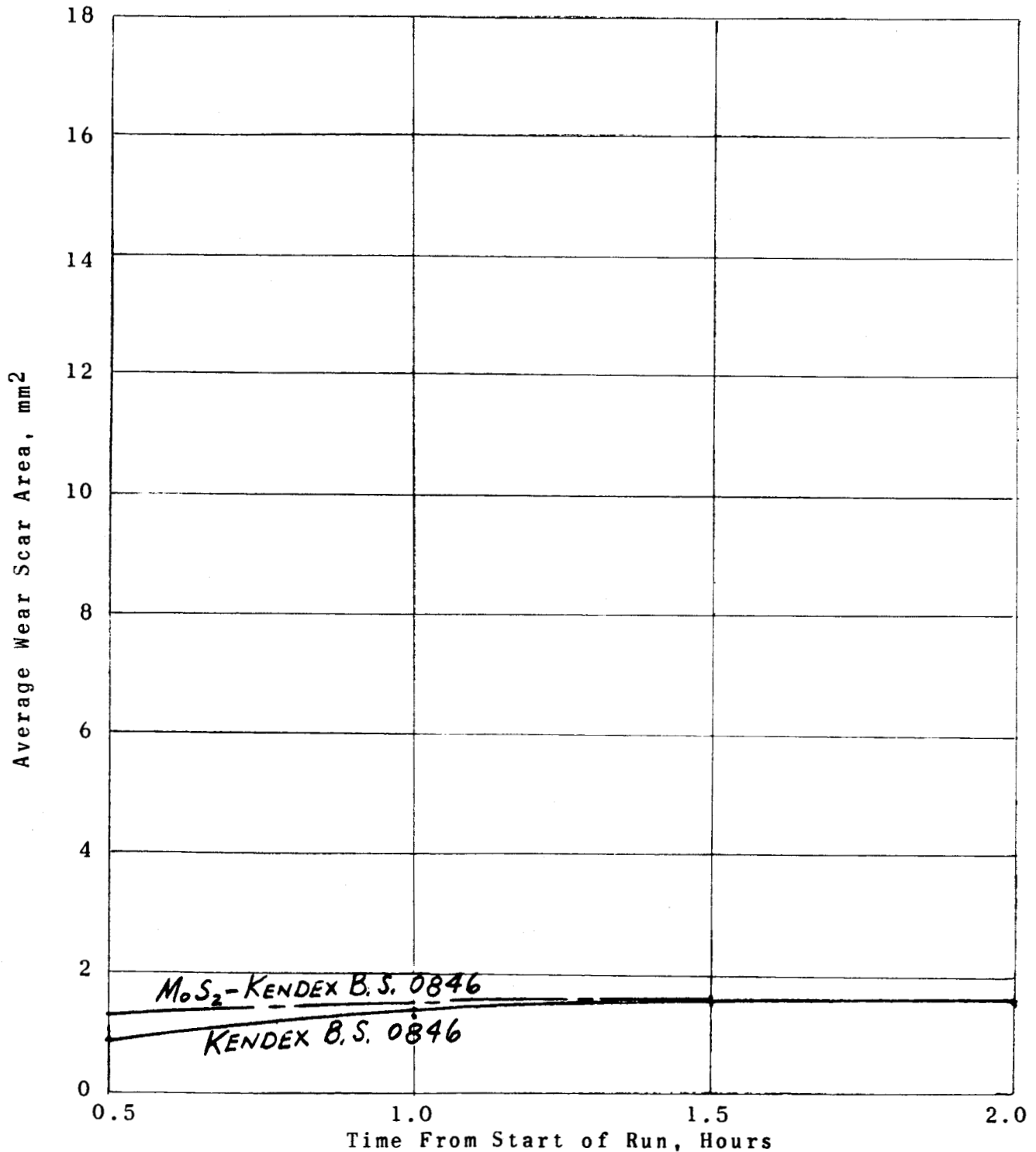


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ENCLOSURE 22

CAGE COMPATABILITY TEST RESULTS WITH S-MONEL (Rc 33) CAGE SPECIMENS
AND LUBRICANTS AS NOTED AT 700°F, 1000 LBS. LOAD AND 1200 RPM

(Average Wear Scar Area Vs. Hour Run)



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